ECMWF

European Centre for Medium-Range Weather Forecasts

Newsletter

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Destination Earth Initiative

Publication policy

The ECMWF Newsletter is published quarterly. Its purpose is to make users of ECMWF products, collaborators with ECMWF and the wider meteorological community aware of new developments at ECMWF and the use that can be made of ECMWF products. Most articles are prepared by staff at ECMWF, but articles are also welcome from people working elsewhere, especially those from Member States and Co-operating States.

The ECMWF Newsletter is not peer-reviewed.

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A wider scope

Weather prediction crucially depends on the ability to determine the state of the atmosphere at the start of forecasts as accurately as possible. Satellite observations play an important role in this, but the use of satellite data has often been limited to clear skies and ocean areas. An article in this Newsletter explains how, in addition to 'all-sky' observations, microwave satellite data can increasingly be used in 'all-surface' conditions. Other articles include a new configuration of the Ensemble of Data Assimilations to be introduced in the next upgrade of ECMWF's Integrated Forecasting System, and promising experiments with assimilating visible radiances despite challenges due to the complex scattering of light. There is also an article on the use by the Israel Meteorological Service (IMS) of ECMWF's high-performance computing facility for research and the development of numerical weather prediction for southeast Europe.

In addition to its weather forecasting activities, ECMWF has agreed to provide part of Destination Earth (DestinE), a new EU initiative to produce an interactive computer simulation of our planet at unprecedented resolution. The other partners are the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). ECMWF's role is to produce 'digital twins' on weather and geophysical hazard-induced extremes and climate change adaptation. It will also develop a digital twin engine, which will be used as a framework to integrate new twins in the future. ESA contributes the core service platform, and EUMETSAT the data repository, called data lake. The history of the initiative is described in this Newsletter. It shows that it is no accident that ECMWF is taking part in DestinE: we were strongly involved from the start, in particular through our Scalability Programme in collaboration with our Member States. DestinE shows how ECMWF's core mission of providing medium-range weather forecasts is an excellent base for wider activities. These also include the EU-funded Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS), which are run by ECMWF, and the Copernicus Emergency Management Service (CEMS), to which ECMWF contributes.

The way in which weather forecasting and environmental services can be intertwined is illustrated in the article on the atmospheric impacts of January's Hunga-Tonga volcano eruption in this Newsletter. Satellite observations showed the immediate impact of the eruption on the atmosphere, but CAMS also monitored the emission of sulphur dioxide and its subsequent spread towards Africa. Weather forecasting also depends on climate data. For example, an article in this Newsletter describes the use of ESA Climate Change Initiative data in ECMWF's Earth system model. But, as another article explains, the same data are also made available to users of C3S in a quality-controlled form. Weather prediction is thus intimately connected to wider Earth system work. Taking on additional tasks relating to DestinE, C3S, CAMS and CEMS is therefore a logical extension of our weather forecasting activities.

Florence Rabier
Director-General

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Wind gust predictions for storm Eunice

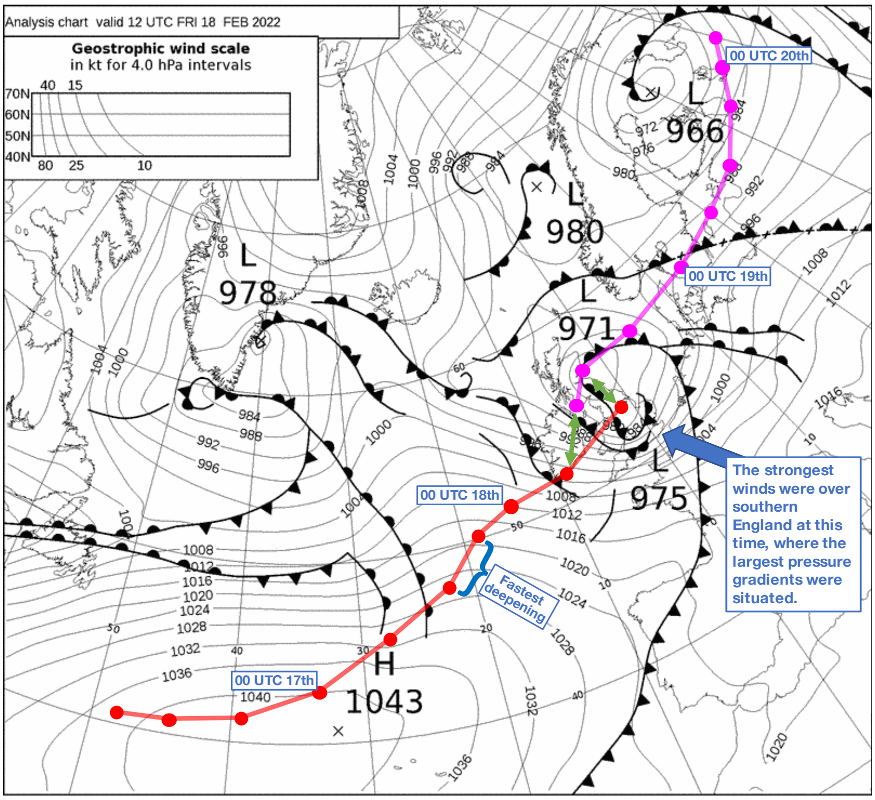
Tim Hewson, Ivan Tsonevsky, Linus Magnusson, Peter Bechtold

The middle of February 2022 was very cyclonic over north-western Europe, with three named storms affecting this area in one week. Cyclone Eunice (also known as Nora and Zeynep) was one of these; it delivered major wind-related impacts in many countries. Here we focus on Eunice and in particular on the gust predictions for the British Isles for 18 February.

Eunice's life cycle

The life cycle of Eunice is represented by coloured tracks on the synoptic chart figure. Eunice started out early on 16 February, in diminutive wave form, on a complex cold front situated west of the Azores. The cyclone then intensified as it translated rapidly east-northeastwards, being driven along in the developmental right-entrance region of an upper level jet. Wind speeds at 300 hPa peaked at around 85–90 m/s, which is strong but not exceptional. As the system crossed the jet core on 17 February, explosive development ensued. The most rapid deepening phase – which for Eunice was approximately 12–18 UTC on 17 February – tends to be just before the risk period for a 'sting jet' in a cyclone's life cycle. This is critical because sting jets tend to lead to exceptional surface wind speeds over land and sea. Indeed, on the evening of 17 February, image sequences of Eunice showed some hallmarks of a sting jet over the Atlantic, notably evaporating cloud head tips, although these only lasted a few hours. The fact that rapid deepening occurred well away from land helped spare the land-based population from the worst of Eunice's winds. Nonetheless, winds associated with the 'cold jet' phase, which follows any sting jet phase and tends to last much longer, did deliver major impacts across northern Europe. In the cold jet phase, one mechanism that fuels downward momentum transfer, to deliver very strong surface gusts, is destabilisation via daytime insolation. Such a process seems to have enhanced gust strength over the south of the UK on 18 February, and over Poland and the Baltic States on 19 February.

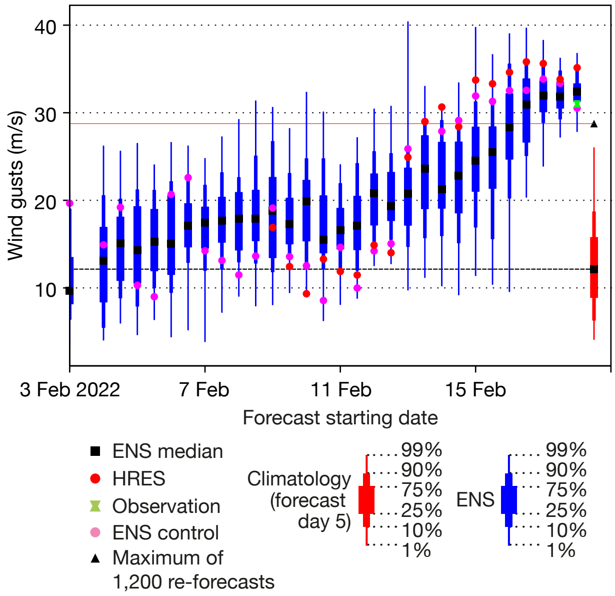
Over the Atlantic, Eunice's life cycle mirrored the classic evolution of an explosively developing cyclone. Over the British Isles, however, there was a departure from this, as the storm split into two centres: the former low (red track on the synoptic chart figure) eventually decayed as a newly developed centre to the north (magenta track) took over. This second centre then continued on an east-northeastward trajectory across northern Europe, eventually decaying about four days after Eunice's genesis.



Synoptic chart and path of Eunice. UK Met Office synoptic chart for 12 UTC on 18 February 2022 (black), when cyclone Eunice had two centres (marked as 971 and 975 hPa lows). The tracks of the two centres are shown in red and magenta (dots at 6 h intervals). Green arrows connect low centres that correspond to the same valid times.

Wind gust forecasts

The forecast evolution figure shows how maximum wind gust forecasts over London Heathrow Airport on 18 February evolved from 3 February. The distribution from the ensemble re-forecast-based model climate valid for forecast day five is shown as the red box-and-whisker symbol, with the maximum in the sample of 1,200 model climate forecast fields highlighted as a triangle.
The maximum observed wind gust at the airport was 31 m/s, according to SYNOP reports. More than a week before the event, the ensemble system predicted a risk for windier-than-normal conditions. The forecast from 12 February already had high Extreme Forecast Index (EFI) values over northern Europe six days ahead. While the signal gradually started to increase in the ensemble for extreme gusts over Heathrow in the next few days, both the high-resolution forecast (HRES) and the ensemble (ENS) control forecast saw a jump towards an extreme level on 13 February. They stayed on the higher end (above the 75th percentile) of the ensemble distribution for the next three days. The lower level of risk implied by the



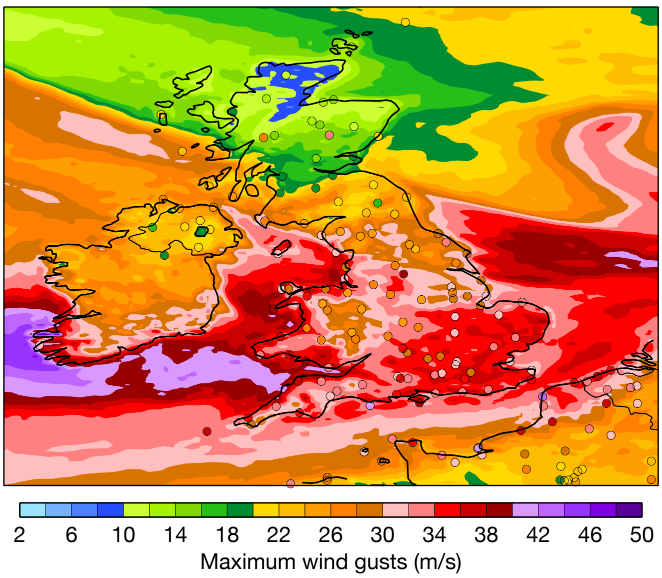
Forecast evolution for London Heathrow Airport. Forecast evolution for 24-hour maximum wind gusts at London Heathrow Airport for 18 February.

ensemble at this stage is notable for this case, but it is impossible to judge the ensemble performance from one specific case. It could have been that this storm was more predictable than appreciated by the ensemble at that stage, favouring the unperturbed members. Ongoing research at ECMWF is investigating whether the ensemble has too much spread during cyclonic conditions.

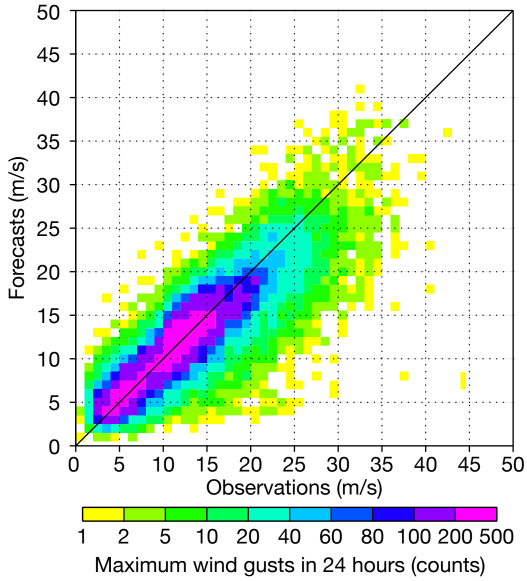
Storm Eunice brought very strong wind gusts of more than 30 m/s quite widely over southern England on 18 February. As can be seen in the plot on predicted and observed maximum wind gusts, the HRES also produced gusts of very high magnitude over the affected areas, but even close to the event HRES gusts were generally a few m/s stronger than observation reports. We will therefore have a closer look at the statistics of the wind gusts during the stormy period (12–20 February). In the Integrated Forecasting System (IFS), wind gusts are computed by accounting for turbulent and convective gustiness using a formula which includes an empirical parameter, C_{ugn}, and a tuning convective mixing parameter, C_{conv}. To address the increasing positive forecast biases in recent years, the computation of wind gusts has been tuned in the current operational cycle of the IFS by reducing C_{ugn} from 7.71 to 7.2 and C_{conv} from 0.6 to 0.3. This change has resulted in reduced forecast biases for wind gusts. As illustrated in the scatter plot image, there is good correspondence between forecast and observations over Europe during the stormy period in February. The gust factor (ratio between gusts and mean wind) also improved – there is a better match between the forecast and observations.

Contrasting errors

Whilst the gust forecast bias is generally small, in individual cases errors of different sign may occur. For example, the overprediction that we saw for Eunice contrasts with an underprediction for storm Franklin, which arrived a few days later, on 21 February. It could well be that different wind-gust phenomena (e.g. sting jet, cold jet, meso-scale convection systems) have different biases, although we must also acknowledge that the accuracy of the synoptic pattern forecast will play a major role for the prediction of wind gusts, with complex evolutions, such as the low-splitting observed for Eunice, being especially challenging.



Predicted and observed maximum wind gusts. Maximum wind gusts in 24 hours from HRES initialised at 00 UTC on 17 February and valid from 18 February at 00 UTC to 19 February at 00 UTC, during the passage of storm Eunice over the UK. Symbols represent observations. This forecast showed substantially higher gusts over southern England than indicated by observations.



Density plot of observed versus predicted wind gusts. The figure shows observed wind gusts versus 24–48 h high-resolution forecast wind gusts over Europe during the stormy period between 12 and 21 February 2022. The forecast bias is close to 0, with the highest density of the observations along the diagonal. Mountain and coastal stations have been excluded.

Forecast performance 2021

Thomas Haiden, David Richardson

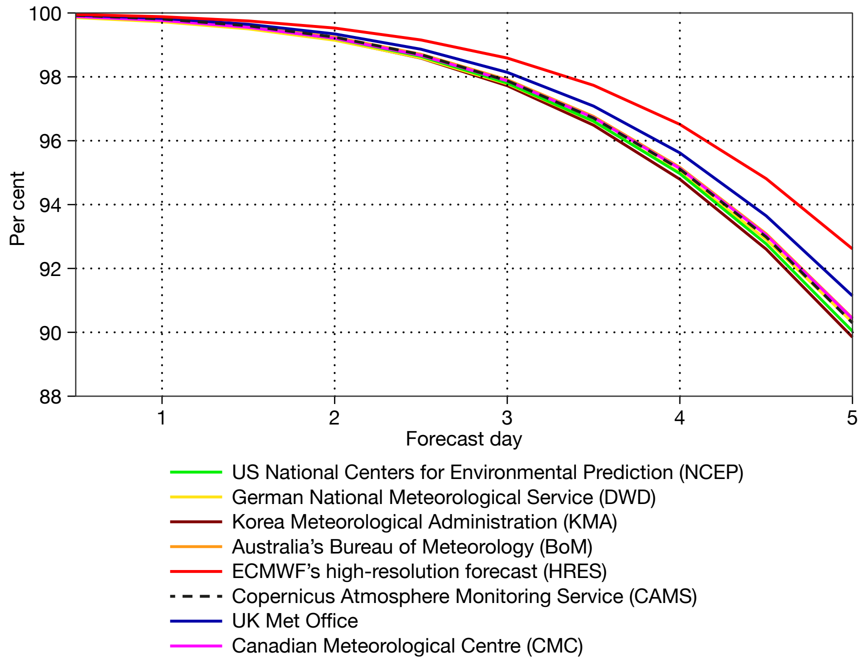
ECMWF maintains a comprehensive range of verification statistics to evaluate the accuracy of its forecasts. Each year, a summary of verification results is presented to ECMWF's Technical Advisory Committee (TAC). Their views about the performance of the operational forecasting system in 2020/21 are given in the box.

In 2021, ECMWF's headline scores showed consistently high values similar to the previous year, while some aspects of forecast skill improved beyond what has been seen before. Compared to forecasts from other global centres, ECMWF has been able to maintain the overall lead for upper-air parameters in the medium range. For surface parameters, especially in the short range, some of the other centres have drawn closer to ECMWF.

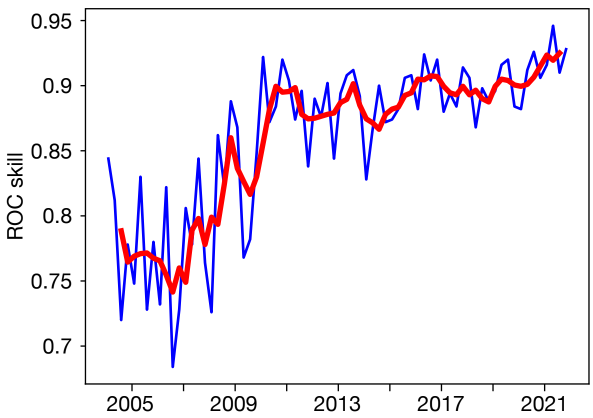
Model Cycle 47r2, implemented on 11 May 2021, brought an increase in the number of levels in the vertical for the ensemble forecast (ENS) to match those of the high-resolution forecast (HRES). The upgrade led to a small but statistically significant improvement in upper-air ENS skill. Model Cycle 47r3, implemented on 12 October 2021, included a major upgrade to the moist physics of the model, resulting in more realistic precipitation characteristics. Together with a number of other changes, this cycle brought small improvements in upper-air skill in the early medium range.

ECMWF has started to routinely monitor the upper-air meteorological forecast performance of the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) run by ECMWF. Its skill is similar to that of other global centres, as seen in the first figure, and the difference between HRES and CAMS at day five amounts to about half a forecast day. The main differences between the two suites, in addition to the treatment of atmospheric constituents, are their initialisation and horizontal resolution.

Position errors for forecasts of tropical cyclones were smaller than in the previous year, but the decrease was paralleled by forecasts based on the ERA5 reanalysis system, which indicates that it was part of natural variability. As in previous years, ECMWF has a modest but consistent lead in ocean wave forecasting over other centres in terms of significant wave height.



CAMS forecast skill compared to HRES and other centres. The chart shows the anomaly correlation of 500 hPa geopotential from different forecasting systems for the northern hemisphere extratropics in the year 2021. The verification is against each centre's own analysis.



Skill of the Extreme Forecast Index (EFI) for 2-metre temperature. The chart shows the relative operating characteristic (ROC) skill at forecast day five in Europe. Three-monthly values are shown in blue and the 12-month running average in red.

There has been a noticeable further increase of the skill of the Extreme Forecast Index (EFI) for 2-metre temperature, as shown in the second figure. After a decade of little systematic change, the ROC skill at day five has recently increased beyond its previous average value of 0.9. There has also been a further significant improvement for 2-metre temperature in week 3, as monitored by the extended-range headline score based on re-forecasts. It is not clear yet how much of the increase is due to inter-annual variability.

ECMWF's seasonal forecast system, SEAS5, predicted the change from La Niña conditions in the equatorial Pacific at the end of 2020 to more

Assessment of ECMWF's Technical Advisory Committee, 6–7 October 2021

With regard to its overall view of the performance of ECMWF's operational forecasting system, the Committee:

a) noted that ECMWF's headline scores continue to show high skill, at least maintaining the level of skill reached in 2019 with some ENS measures reaching their highest ever scores;

b) noted that evaluation of extended-range real-time forecasts for 2 m temperature anomalies shows some increase in week 2 and a little improvement in skill at week 3 and 4 in winter;

c) recognised that ECMWF maintains a lead compared to other centres in terms of upper air medium- and extended-range ensemble spread and error, though there remains some under-dispersion in the summer;

d) recognised that ECMWF has an overall lead in verification scores against buoys for extratropical ocean wave height but not for peak period;

e) recognised that EFI ROC and Diagonal Elementary skill scores over Europe aimed at high-impact weather showed new high points for skill at Day 5 were reached for 2 m temperature, 10 m wind speed and 24 h precipitation; in the case of 2 m temperature this is especially pleasing as there seemed to have been a plateau in skill over the last 10 or so years;

f) noted that skill scores for mean position errors of tropical cyclones on Days 3 and 5 are not as low as 2019, but improved relative to ERA5 and the gap between HRES and ERA5 for intensity and speed has been maintained;

g) noted that ECMWF's seasonal forecasts joined other models in underestimating magnitude of La Niña and then was too slow in initially returning to a neutral ENSO;

h) noted that the winter 2020/21 SEAS5 forecast missed the cold anomaly over northern Siberia and then missed magnitude of colder conditions late winter/early spring, more so over northern Europe. The summer 2021 SEAS5 forecast did not capture the magnitude of warm anomaly over northern Europe but was better with details over southern Europe;

i) noted that CAMS, for meteorology, ranks third behind other centres, including the HRES, and can be better than the HRES at times in some areas of the Tropics where biomass burning plays a role due to having prognostic, interactive aerosol;

j) noted that some users would like additional Europe-centric verification for ENS scores, perhaps including comparison with other centres;

k) congratulated ECMWF on the successful implementation of IFS Cycle 47r2 in May 2021, which included a move to single-precision for both the ENS and HRES and an increase in ENS vertical resolution to 137 levels which led to an improvement in ENS verification scores;

l) congratulated ECMWF on the successful implementation of Open Charts in October 2020 and welcomed ECMWF's commitment to responding to user feedback in further developing Open Charts;

m) welcomed the implementation of IFS Cycle 47r3 scheduled for October 2021, recognising that components such as the major upgrade to moist physics will aid the forecasting community in many ways, for example improved precipitation, whilst also providing a stronger foundation to move to higher resolution models in the future. Appreciated the many other improvements 47r3 brings, noting that some of these improvements have been driven by user feedback;

n) appreciated the support ECMWF has given in developing some new products, for example ecPoint, and welcomed further developments with post-processing and machine-learning;

o) welcomed the improvements to CAMS, the ongoing development of the Climate Data Store and ECMWF's commitment to maintaining the integrity and quality of their contributing elements to C3S;

p) welcomed proposed improvements at 48r1 in late 2022/early 2023, noting that data volumes will then also change as ENS horizontal resolution improves and the extended range commences running with 100 members daily;

q) appreciated the training, documentation and feedback processes provided by ECMWF and welcomed future training opportunities and webinars introducing new products and developments;

r) appreciated the continued very good support ECMWF provided to Member and Co-operating States over the last year, particularly in the face of COVID-19 when training and events such as the annual UEF continued.

neutral conditions in 2021 reasonably well, although the change occurred somewhat earlier than predicted. Due to the absence of strong tropical forcing during most of 2021, the skill of the extratropical seasonal forecast was relatively low.

The complete set of annual verification results is available in ECMWF Technical Memorandum No. 884 on 'Evaluation of ECMWF forecasts, including the 2021 upgrade', downloadable from http://www.ecmwf.int/en/publications/technical-memoranda.

The following are other sources of information about verification and forecasting system changes:

- Verification pages: https://apps.ecmwf.int/webapps/opencharts/
- Inter-comparison of global model forecast skill: http://apps.ecmwf.int/wmolcdnv/
- Ocean wave model inter-comparison results: https://confluence.ecmwf.int/display/WLW/WMO+Lead+Centre+for+Wave+Forecast+Verification+LC-WFV
- A list of 'Known IFS Forecasting Issues': https://confluence.ecmwf.int/display/FCST/Known+IFS+forecasting+issues
- IFS forecasting system cycle changes since 1985: http://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

Soft re-centring Ensemble of Data Assimilations

Elías Hólm, Massimo Bonavita, Simon Lang

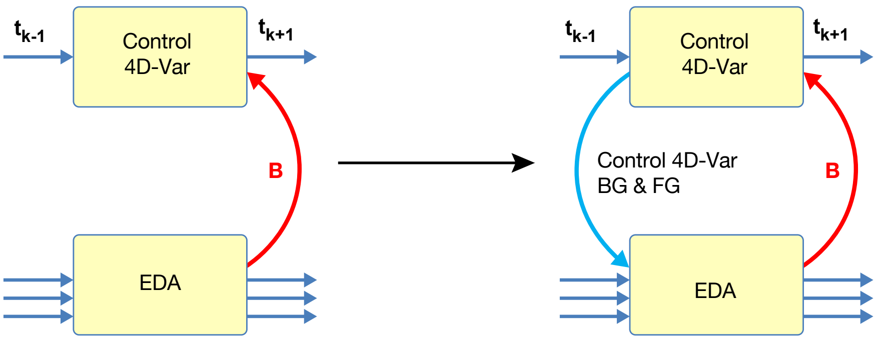
The Ensemble of Data Assimilations (EDA) will in Cycle 48r1 of the Integrated Forecasting System (IFS) change to a more accurate and computationally efficient configuration we call a 'soft re-centring EDA'. In this new configuration, the EDA is approximately 30% cheaper to run than the current EDA for the same resolution. This computational saving will make the increase in resolution of the EDA also planned for Cycle 48r1 affordable.

Soft re-centring to improve analysis accuracy

In the EDA, we have an ensemble of perturbed members that are used to prepare a background error covariance matrix **B** for the next analysis cycle and that are also part of the initial conditions of ensemble forecasts (ENS).
In addition, the EDA has an unperturbed control analysis that provides some information to perturbed members' analyses, such as observation bias correction and 'pre-conditioning' information that speeds up a perturbed member's analysis.

Re-centring is a commonly used technique in ensemble assimilation and forecasting. It regards ensemble members as perturbations from their mean, which are added to a more accurate re-centring state as a post-processing step. This improves the accuracy of the ensemble. We do this when initialising ENS from EDA forecast perturbations added to the latest available high-resolution 4D-Var analysis. We have so far not used re-centring in the EDA itself to improve the analysis of perturbed members. However, when we looked in detail, we found that we could improve the starting state of the perturbed members' analyses by incorporating information from a more accurate control analysis.

The 'soft re-centring' concept comes from incorporating information from the control member as input to a perturbed member's analysis, rather than taking a perturbed member's output and re-centring it on the control member's analysis ('hard re-centring'). In a soft re-centring EDA, the control analysis thus becomes part of the cycling of the perturbed members' analyses (see the figure). In soft re-centring, the control member's analysis is run in a 4D-Var configuration with three 9 km outer loops with 50 km/50 km/40 km minimisations, closer to the high-resolution (HRES) 4D-Var. The gain in accuracy makes it possible to run perturbed members with a cheaper 4D-Var configuration with only one 9 km outer loop with 40 km minimisation, without loss of overall accuracy. Additionally, the fact that the re-centring is done inside the 4D-Var minimisation helps to significantly reduce initial imbalances.



Soft re-centring adds feedback from control member analysis to improve perturbed members' analyses. In a soft re-centring EDA, information from the control member is added to the background (BG) and first-guess (FG) of the perturbed members' analyses and thus becomes part of the cycling of their analyses. **B** is the background error covariance matrix, which provides the weight of the model state in the analysis. All members have 9 km outer loops, with perturbed members having single 40 km minimisation and the control member three minimisations at 50 km/50 km/40 km resolution.

How does soft re-centring integrate the control member analysis? After the first minimisation of the control member has finished, the perturbed members' analyses start, incorporating the additional information from the control's preliminary analysis. First, the difference between control and ensemble mean background state is added to the background of all perturbed members, re-centring the perturbed members on the control background. This step improves the accuracy of the EDA mean analysis. The second step is to add the control member preliminary analysis increment to the perturbed members' re-centred background to give a first guess trajectory that on average moves each member's first guess closer to the final analysis solution. This second step is analogous to what we already do in the continuous long-window data assimilation (Co-LWDA) introduced in the HRES 4D-Var in IFS Cycle 47r1 (see the article by Hólm et al. in ECMWF Newsletter No. 163), where the early-delivery analysis is used as first guess in LWDA. In summary, the control member shows the perturbed members' analyses how on average to account for new observations, and soft re-centring includes this average information as a starting point for the perturbed members' analyses. The new control is not just an unperturbed member of the EDA as previously, but effectively an HRES clone (though not yet in real time), and it paves the way for a future tighter coupling of HRES 4D-Var and the EDA.

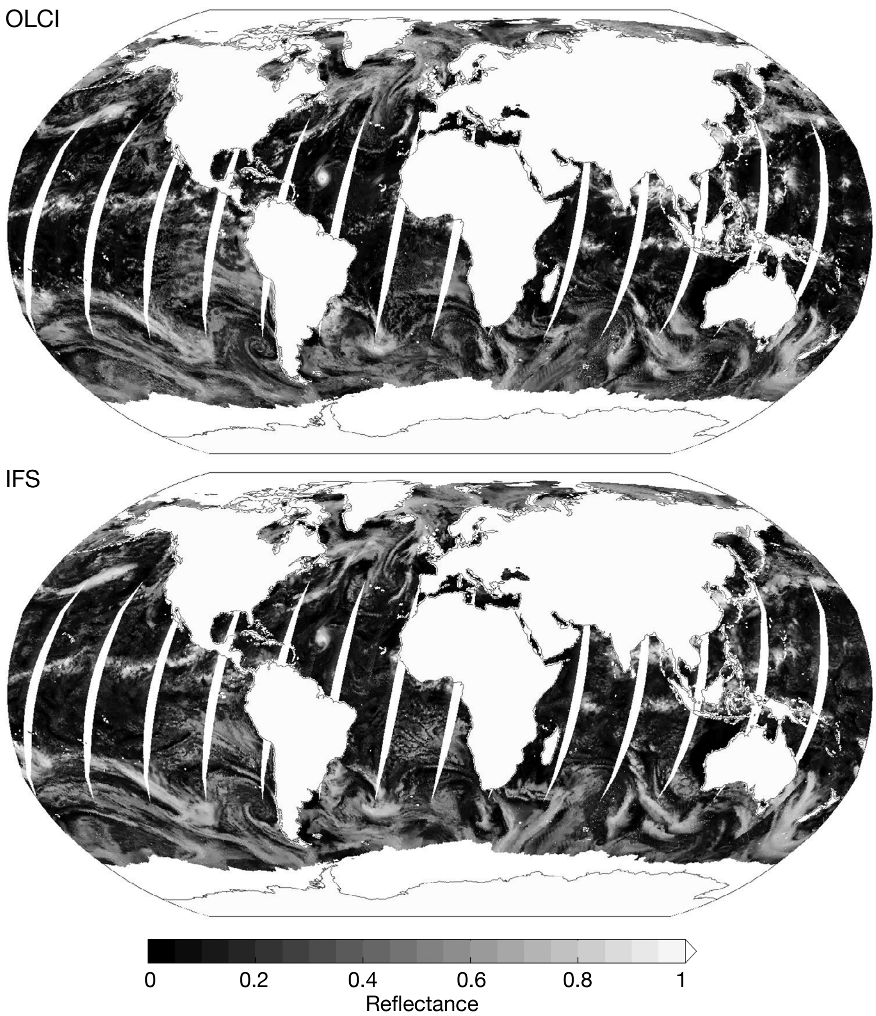
Effect on forecast performance

In terms of forecast performance, the soft re-centring EDA brings a small but visible improvement in the EDA control. This comes from more consistent estimates of the background error covariance matrix **B**. There are large improvements in the forecast skill of individual EDA members and an increase in spread of the whole EDA, which are visible when we start an ENS forecast directly from the EDA initial conditions. Some of these improvements remain visible also in the operational-like ENS setup, where 6-hour EDA forecasts are hard re-centred on the control analysis and singular vectors are also added.

Initial results of monitoring cloudy visible radiances

Liam Steele, Angela Benedetti, Marco Matricardi, Alan Geer, Peter Lean

Visible radiances contain a wealth of information on clouds. They are available at high horizontal resolution and are sensitive to the full depth of clouds in the atmosphere. However, assimilating visible radiances poses challenges due to the complex scattering of light. As such, they have never been assimilated in global numerical weather prediction models. ECMWF is currently performing monitoring experiments of cloudy visible radiances, as a first step towards their possible future implementation in operational data assimilation. In monitoring experiments, the first-guess departures (the differences between the observations and the model background) are calculated, but they are not used to adjust model fields in the assimilation.



Global comparison between observed and predicted reflectances. OLCI observations for 5 September 2021 are shown in the top image and short-term IFS predictions in the bottom image.

Visible radiance data

For the monitoring experiments, we are using data from the Ocean and Land Colour Imager (OLCI) instruments, OLCI-A and OLCI-B, which are aboard Sentinel-3A and Sentinel-3B respectively. The data have a swath width of 1,270 km at nadir, with a ground spatial resolution of 300 m. We are using data at a wavelength of 665 nm, as this is little affected by absorption in the atmosphere, so there is only a minor impact on the reflected solar radiation.

To enable comparisons against predictions of ECMWF's Integrated Forecasting System (IFS), we convert the spectral radiances into reflectances. The data are transformed ('superobbed') to a resolution of 30 km, as this more closely resembles the resolution of the monitoring experiments. Due to the complexities of the scattering of visible radiation from land and ice surfaces, we are only using data over ice-free oceans.

To calculate reflectances in the IFS, we are using the Method for Fast Satellite Image Synthesis (MFASIS), which is based on a reflectance look-up table. For MFASIS, the state of the atmosphere is described by only a few parameters: total optical depths, and vertically-averaged effective radii of liquid water and ice.

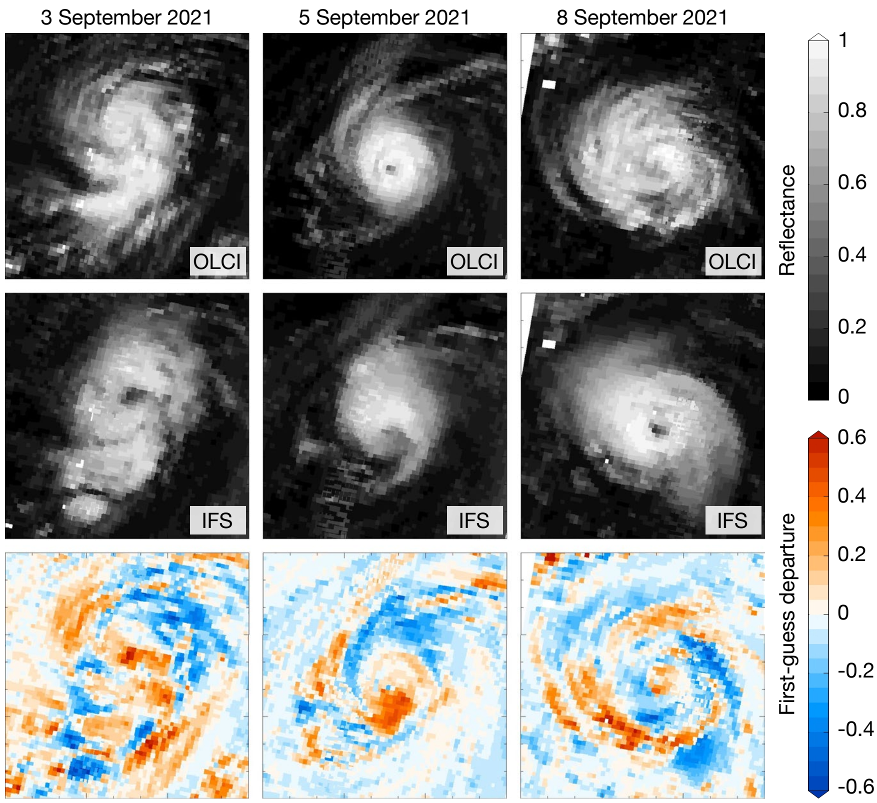
Preliminary results

Experiments have been performed to monitor cloud prediction during September 2021. As the edges of cloudy regions tend to have sharp gradients in reflectance, the first-guess departures reveal where clouds in the IFS, and hence temperatures or humidities, are likely to differ from reality. The majority of the large-scale synoptic cloud features are represented in the IFS, particularly clouds along frontal boundaries. The locations of large areas of convection, such as those in the Intertropical Convergence Zone, are also captured well, though the IFS reflectances tend to be lower. Smaller-scale cloud features, such as individual convective cells or regions of altocumulus, tend to be less well captured.

The monitoring period includes Hurricane Larry, which began as a tropical storm on 1 September and reached peak intensity as a category 3 hurricane on 5 September, with winds of 125 mph. In general, the location of the hurricane in the IFS is in close agreement with the observations throughout its lifespan, although the presentation of the eye and the structure of the cloud bands show some discrepancies.

Outlook

The monitoring experiments performed so far reveal the potential benefit of visible data assimilation. The first-guess departures provide information ranging from the large scale, such as highlighting where regions of frontal clouds are located, to the smaller scale, such as revealing the structure of hurricanes and convective cells. While the analysis here has been performed with 30 km resolution data, visible data are available at much higher resolutions. Thus, as the resolution of forecasting models increases over time, it is possible that even more benefit can be obtained from the observations, as the structure of smaller-scale cloud features in models improves. While there are many instruments operating today that could be used for visible data assimilation, there is also a wealth of visible observations stretching back many decades, which could be exploited for reanalysis applications. Thus, there appears to be great potential for visible data assimilation.



Observed and predicted reflectances of Hurricane Larry on three separate days. The top row shows reflectances from the OLCI observations, while the middle row shows short-term IFS predictions. The bottom row shows first-guess departures (observations minus model background). Each panel covers 15° in latitude and longitude.

ECMWF participates in Atmospheric River Reconnaissance

David Lavers (ECMWF), Anna Wilson, Marty Ralph (both Scripps Institution of Oceanography, US), Ryan Torn (University at Albany, State University of New York, US), Florian Pappenberger (ECMWF)

In early 2022, ECMWF participated in the Atmospheric River Reconnaissance (AR Recon) observational campaign in the northeast Pacific. For ECMWF, the AR Recon campaign is important because the observations gathered improve the initial atmospheric conditions of ECMWF's Integrated Forecasting System (IFS), and hence medium-range forecast skill. They also afford opportunities for diagnostic studies of the forecast system. Over the course of the campaign, ECMWF provided input to the weather forecast briefings which were used for flight planning, helped to identify the locations for the ocean buoy deployments, and undertook real-time monitoring of the observations assimilated into the IFS.

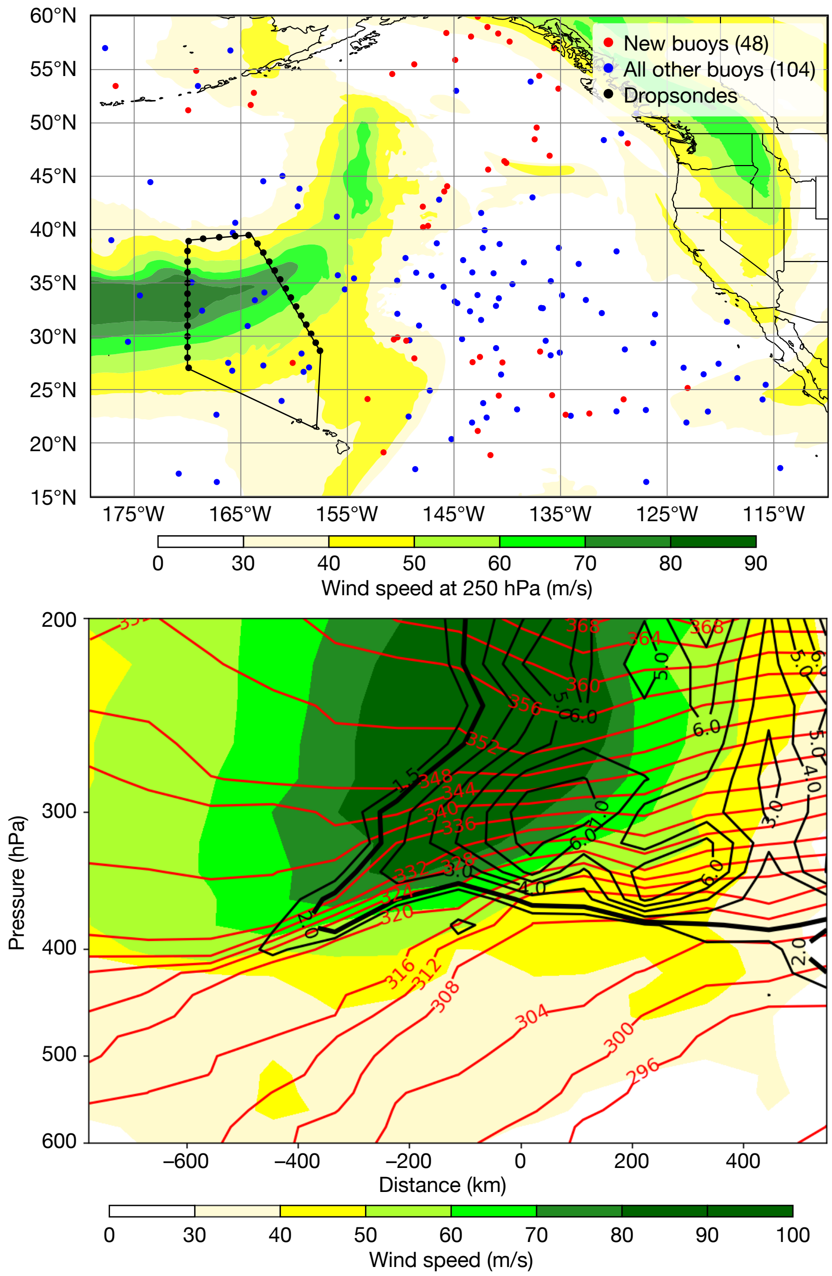
The aim of AR Recon is to improve the forecast skill of landfalling atmospheric rivers and their impacts to better inform the decision-makers who are responsible for water management and flood preparedness in the western United States.
To achieve this objective, AR Recon has been set up as a Research and Operations Partnership by the Center for Western Weather and Water Extremes (CW3E) at Scripps Institution of Oceanography and the US National Weather Service/National Centers for Environmental Prediction. Its core partners include the US Naval Research Laboratory, the NOAA (National Oceanic and Atmospheric Administration) Aircraft Operations Center, the US Air Force Reserve Command, the National Center for Atmospheric Research, ECMWF, and multiple academic institutions.
The campaign is also formally incorporated in the US National Winter Season Operations Plan.
Although AR Recon currently has a northeast Pacific focus, any forecast improvements made in this domain have downstream benefits for Europe and the whole IFS.

Scope of the deployment

In the 2022 season, 50 drifting ocean buoys were deployed in the northeast Pacific via (1) a ship of opportunity from Los Angeles to Honolulu and from Honolulu to San Francisco and (2) US Air Force

Reserve Command flights (see the top figure). The sea-level pressure observations from these buoys were assimilated into the IFS shortly after their release, and they will continue to be used over the operational lifetime of the buoys, which can exceed two years. The Lagrangian Drifter Laboratory and CW3E, both at Scripps Institution of Oceanography, led the deployment planning, with funding from the NOAA Global Drifter Program (https://gdp.ucsd.edu/ldl/global-drifter-program/), the California Department of Water Resources, and the U.S. Army Corps of Engineers. Two types of buoys were deployed: 10 Directional Wave Spectra Barometer drifters (DWSB; https://gdp.ucsd.edu/ldl/dwsbd/) and 40 Surface Velocity Program Barometer drifters (SVPB; https://gdp.ucsd.edu/ldl/svpb/). Like the SVPB drifters, the DWSB drifters measure sea-surface temperature and barometric pressure. However, DWSB drifters also compute the directional wave spectrum via a high-performance GPS engine. The locations of the new buoys – 48 of which were seen by the IFS on 21 February 2022 – are shown by the red markers in the figure. These add to earlier buoy deployments as part of AR Recon (Newsletter No. 159 and No. 163).

In addition to the buoy deployments, a number of dropsondes were also deployed during intensive observing periods (IOPs). Each IOP, which has up to three aircraft flying simultaneously, releases dropsondes to collect observed atmospheric profiles of the specific humidity, temperature, and winds. The locations of the dropsondes in an IOP centred on 00 UTC 3 February 2022 are shown by the black markers in the top figure. During a flight out of Honolulu, the NOAA G-IV aircraft deployed 30 dropsondes across the jet stream, where a wind speed of over 100 m/s was observed. This IOP will provide a unique opportunity to evaluate the jet stream structure in the IFS at various lead times. The cross section through the jet stream along 170°W longitude, as constructed with the dropsonde observations, is shown in the bottom figure. This cross section features a prominent upper-level front that extends down to 400 hPa underneath the jet, and this feature was not well represented in model analyses and forecasts (not shown).



New drifting buoys and an IOP in the northeast Pacific. The top figure shows the location of all drifting buoys that reported pressure in the northeast Pacific Ocean on 21 February 2022. Red markers refer to the newly deployed AR Recon drifting buoys. The 250 hPa wind speed (m/s) in the IFS analysis at 00 UTC on 3 February 2022 is also shown. The black line represents the NOAA G-IV aircraft flight track and the black markers are the dropsonde locations during the IOP on 3 February 2022. The bottom figure is a cross section of the jet stream along 170°W, as constructed with the dropsonde observations, on 3 February 2022. The shading is the wind speed, red contours are the potential temperature (K), and black contours are the potential vorticity (PVU). Note that the north is on the right-hand side of the cross section, so that the wind is coming out of the page. The x-axis shows the distance relative to the maximum jet stream wind.

Previous AR Recon diagnostic studies at ECMWF can be found in Lavers et al. (2018; doi.org/10.1029/2018GL079019) and Lavers et al. (2020; doi.org/10.1175/WAF-D-20-0049.1). Further information on the pressure observations from drifting buoys is available in Ingleby & Isaksen (2018; doi.org/10.1002/asl.822) and Centurioni et al. (2017; doi.org/10.1175/BAMS-D-15-00080.1).

Use of ESA Climate Change Initiative data in ECMWF's Earth system model

Angela Benedetti, Gianpaolo Balsamo, Souhail Boussetta, Francesca Di Giuseppe, Antje Inness, Kenta Ochi, Patricia de Rosnay, Hao Zuo

Climate change and consequent changes in weather patterns are among the greatest environmental challenges of the 21st century. The implications of a warming climate are widespread, affecting fresh water resources, global food production and sea levels.

The need for systematic observations of climate over a significant timescale has never been greater than today. To respond to this need, in 2012 the European Space Agency (ESA) launched the Climate Change Initiative (CCI) programme, which is currently in its third phase. The objective of CCI is to realise the full potential of the long-term global Earth observation archives that ESA has established over the past 30 years. For more information, see https://climate.esa.int/en/.

At ECMWF, several CCI datasets are used for various applications within our Earth system model. Here we briefly present some examples.

Ocean CCI datasets

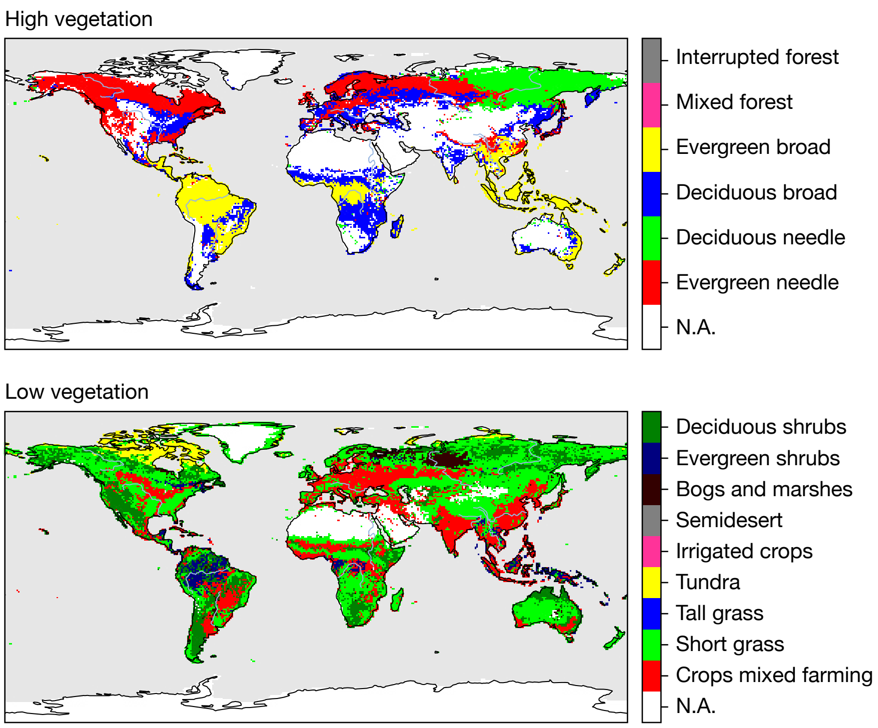
Various ocean-related climate data records have been developed during the last two phases of ESA-CCI projects. These include L4 gridded sea-level (SL) anomalies, sea-surface temperature (SST) analysis, sea-surface salinity (SSS) analysis, and sea-ice data (concentration and thickness). These CCI climate data were developed with a focus on reconstructing accurate and homogenous long-term climate signals by using consistent reference satellite instruments throughout the full reprocessing period. As a result, these CCI datasets are commonly used for monitoring and tracking climate change signals related to the ocean. At ECMWF, they have been used for verification of seasonal forecasts and for evaluation of the performance of ocean and sea-ice reanalysis systems. Research activities to investigate direct assimilation of CCI ocean data, such as SST and sea-ice thickness data, in the ECMWF ocean reanalysis system are ongoing as well.

Land CCI datasets

An upgrade to more accurate and up-to-date land use and land cover (LU/LC) maps is being tested within the ECMWF system. This uses a new software framework to generate the model physiography for the ECMWF land surface modelling system (ECLand). The new maps are based on the ESA-CCI LU/LC, which provides consistent maps at 300 m spatial resolution on an annual basis from 1992 to the present. A total of 22 land cover classes are represented, based on the land cover classification system developed by the United Nations Food and Agriculture Organization, and adapted to the Biosphere-Atmosphere Transfer Scheme classes used in ECLand. The introduction of ESA-CCI maps will increase low vegetation and bare ground covers and reduce high vegetation cover. These differences will have a substantial impact on energy, carbon and water fluxes, which are currently being evaluated for future operational implementation.

Snow CCI dataset

ECMWF is part of the Snow CCI Climate Research Group. Preliminary investigations have shown a good level of consistency between the prototype snow cover CCI products and the IMS (Interactive Multisensor snow and ice mapping System) snow cover from the United States National Ice Center that is currently assimilated at ECMWF for numerical weather prediction and reanalysis. However, IMS high-resolution snow cover is available from 2004 only. This results in a discontinuity in snow cover and snow mass in ECMWF's ERA5 reanalysis in 2004. The quality of the CCI snow cover product from the early 1980s opens up possibilities to



ESA-CCI vegetation type maps adapted to ECLand. The charts are for high vegetation (upper panel) and low vegetation (lower panel).

investigate CCI snow cover product assimilation in ECMWF's Integrated Forecasting System for future reanalysis activities.

Fire CCI datasets

It is estimated that about 25%–35% of greenhouse gas emissions result from biomass burning, making the monitoring of fire disturbance a crucial aspect of the climate system. To this end, Fire CCI focuses on the key variable 'burned area'. It incorporates active fire observations as a supplemental variable to improve detection and reduce latency time, which previously precluded the possibility of using these observations in real time. An ESA-funded study looked at the potential of using Fire CCI to quantify the total fuel released during a fire. It demonstrated that, by directly combining above-ground biomass retrievals and burned areas from Fire CCI, fire emissions improved, leading to a better analysis of aerosol optical depth. Given the impact that biomass burning aerosols have on the energy budget of the planet, this could in turn lead to improved weather forecasts and consequently better skill in downstream applications that rely on it.

Atmosphere CCI datasets

Ozone CCI datasets have been investigated extensively and used in ERA5. Dedicated round-robin assimilation experiments were performed, aiming to identify the best candidates for ERA5. Detailed assessment studies were also performed to evaluate possible synergies of using ozone products derived from instruments with different characteristics. A range of CCI data were also used in the latest reanalysis (EAC4) provided by the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) run by ECMWF, including O_3 products from the SCIAMACHY, MIPAS and GOME-2 instruments, as well as CO_2 and CH_4 products from SCIAMACHY and TANSO. More recently, ESA-CCI Sentinel-5P ozone data have been used in tests to assess their value for the operational ECMWF numerical weather prediction analysis. These tests have demonstrated a good level of readiness of the data and positive impacts on the fit to other observations. The operational S5P ozone retrieval, produced with an algorithm developed by the German Aerospace Center (DLR), is already used in the global CAMS near-real-time system and the CAMS reanalysis.

Aerosol optical depth (AOD) CCI retrievals from the AATSR sensor on board the Envisat satellite have been successfully assimilated in the CAMS reanalysis. More recently, AOD data from the successor multi-angle instrument SLSTR on board Sentinel-3 satellites has been investigated in the CAMS configuration. Results of assimilation tests showed that the product had not yet reached the desired maturity level for use in the next CAMS reanalysis. A new version of the retrieval with enhanced features will be released in the next few months.

ESA-CCI Essential Climate Variables in the Climate Data Store

Carlo Buontempo, Chiara Cagnazzo, Joaquin Muñoz Sabater, André Obregón, Iryna Rozum, Freja Vamborg

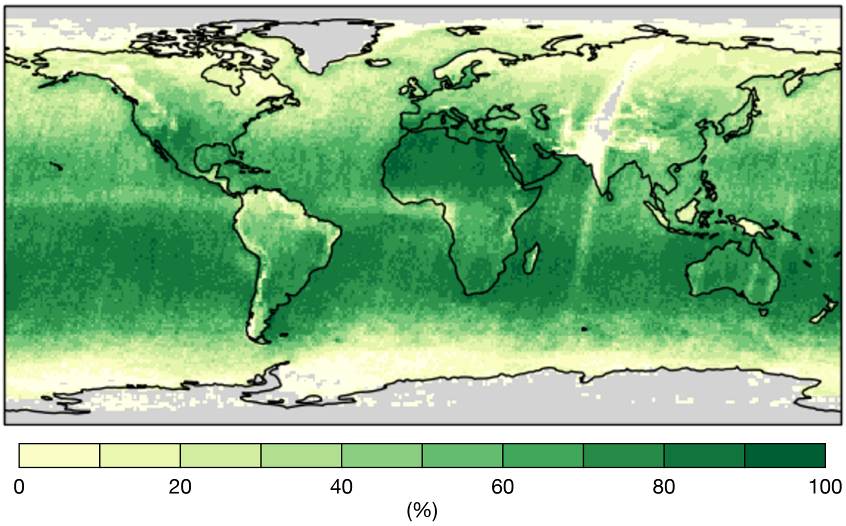
The Copernicus Climate Change Service (C3S), implemented by ECMWF on behalf of the EU, delivers open and free access to state-of-the-art climate products and information, building upon the latest science. Among different climate data, C3S provides operational services for 22 satellite-based essential climate variables (ECVs). This includes access to derived products, generally in the form of global gridded Climate Data Records (CDRs) through the cloud-based Copernicus Climate Data Store (CDS). A subset of them is delivered in coordination with the European Space Agency Climate Change Initiative (ESA-CCI), where C3S operationalises the ESA-CCI production chains to generate seamless temporal extensions of CDRs. An interactive application displaying variables from ESA-CCI CDRs together with reanalysis variables is under development in the CDS Toolbox. Selected ECVs from ESA-CCI are already routinely used, while others are planned to be used, in the C3S European State of the Climate report and other C3S monitoring activities. They include concentration of greenhouse gases, sea-ice thickness, sea level, sea-surface temperature and ocean colour.

C3S quality control

Together with access to the data, C3S has developed an Evaluation and Quality Control (EQC) framework to assess the technical and scientific quality of different service components, including datasets, applications and tools, with special attention to their value to the users.

The EQC function includes independent scientific assessment of ECV products from satellite observations available through the CDS, including CDRs from ESA-CCI. Those independent assessments are made by scientific experts and complement the evaluations prepared by data providers, by focusing on several aspects such as documentation, data accessibility, usability and dataset maturity.

EQC reports include, for each evaluated dataset: (i) an evaluation of technical characteristics (such as metadata standards, data format, space-time resolution and coverage (an example of coverage is given in the figure); (ii) a section on dataset maturity, focusing on data documentation and uncertainty characterisation and based on a substantial literature review by the evaluators; (iii) a fitness for purpose analysis in the context of specific scientific applications, including dataset homogeneity, its capability to reproduce known climate extremes, and its ability to estimate linear trends.



Data availability plot. This plot indicates data availability as a function of latitude and longitude aggregated over the period June 1995 to June 2003 of aerosol optical depth at 550 nm provided by the ATSR2-SU-V4.32 monthly dataset. Grey regions denote pixels for which no data is available.

The fitness for purpose function is generated through the analysis of single CDRs (quality reports of single products) and by looking at consistency across same products from different data sources (quality reports of multi-products).

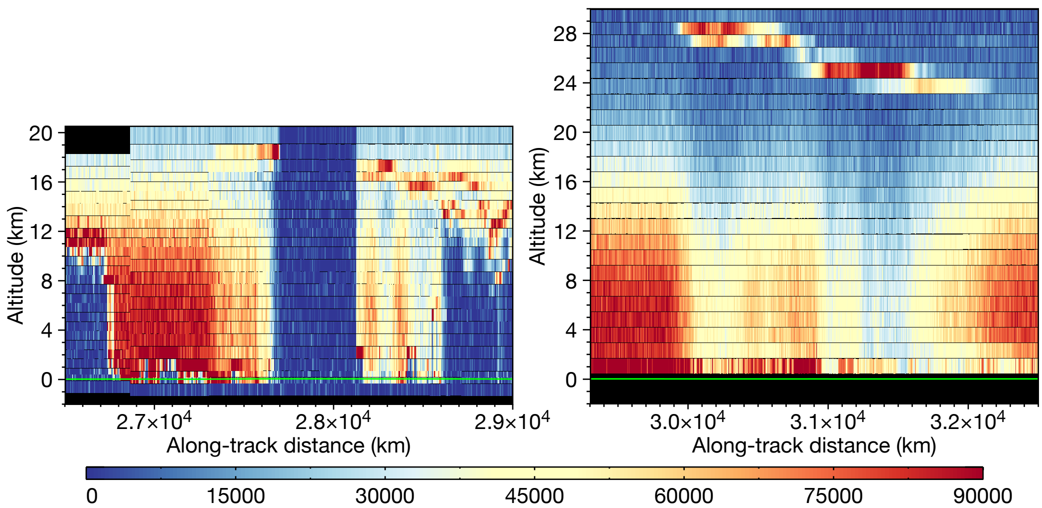
ESA-CCI and C3S programmes rely on the European scientific community. With complementary objectives, they address the needs of the United Nations Framework Convention on Climate Change for data about climate change and information to support adaptation. Close coordination between the two programmes ensures that, for products available in the CDS, the latest research and development from the ESA-CCI science-driven activities is represented and the production chains are operationalised and transformed into services by C3S.

Monitoring the atmospheric impacts of the Hunga-Tonga eruption

Mark Parrington, Michael Rennie, Antje Inness, David Duncan

The eruption of the Hunga Tonga–Hunga Ha'apai volcano in the southern Pacific Ocean on 15 January 2022 had a strong effect on the signals of several satellite instruments used by ECMWF, both for numerical weather prediction (NWP) and atmospheric composition. As widely reported at the time, this was a powerful eruption that could be heard thousands of kilometres away. At the time, signals evaluated by ECMWF showed that the plume rose higher than 20 km.

Atmospheric impacts of volcanic eruptions are most clearly observed in terms of the ash column, which in the case of Hunga-Tonga was observed in satellite imagery to reach well into the stratosphere and beyond (https://earthobservatory.nasa.gov/images/149474). Particulate matter in the ash column was first detected as a significant reduction in measurements from the European Space Agency's Aeolus satellite, which uses the amplitude of back-scattered lidar pulses at 355 nm by aerosol particles (and clouds and air molecules) to profile atmospheric winds using the Doppler frequency shift. The top altitude of the Aeolus measurements, at 21 km, was below the altitude of the ash plume, causing the total attenuation of the lidar pulses. The range of the Aeolus measurements was raised to 30 km later in January, after which the satellite's cloud observations clearly reflected the

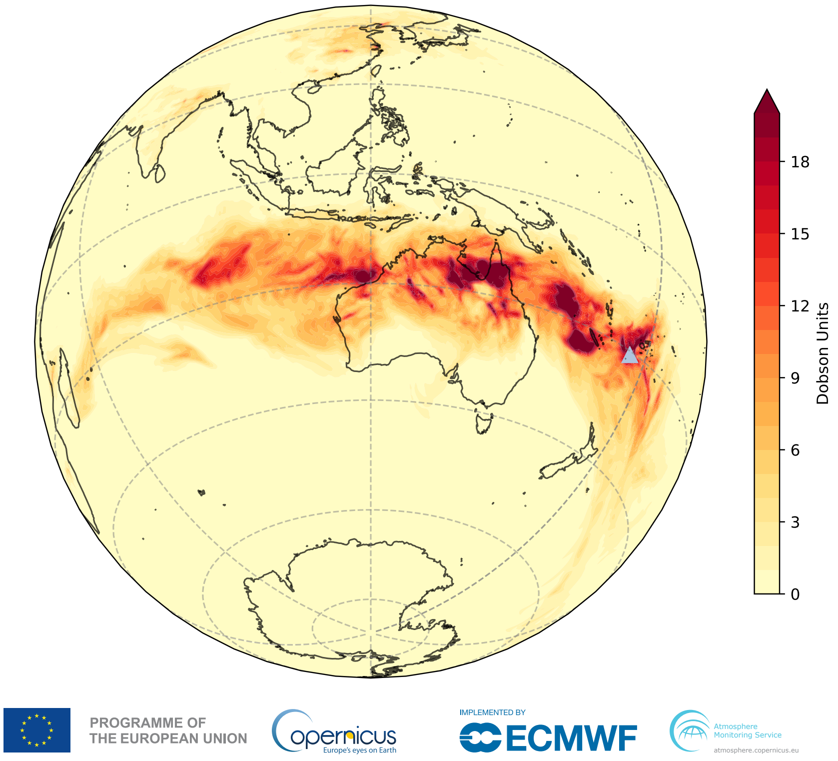


Aeolus observations on 15 and 24 January 2022. Aeolus backscattered signal levels (Rayleigh channel) as a function of horizontal distance and altitude for part of an orbit on 15 January 2022 just after the eruption (left) and on 24 January after the plume had been advected/dispersed by tropical stratospheric winds (right). For the second plot, the Aeolus instrument was adjusted to reach 30 km to capture the plume.

location of the ash plume in the stratosphere (see the Aeolus figures).

Another atmospheric impact of volcanic eruptions is through emissions of sulphur dioxide (SO_2). Total column SO_2 abundance in the atmosphere can be detected by the Metop/GOME-2 and Sentinel-5P/Tropomi satellite instruments using observations of back-scattered solar radiation at ultraviolet and visible wavelengths. The Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF for the EU, assimilates satellite observations of total column SO_2 in ECMWF's Integrated Forecasting System (IFS) following a volcanic eruption to provide analyses and forecasts (see Inness et al., https://doi.org/10.5194/gmd-15-971-2022). It observed the transport of SO_2 initially across the South Pacific and later across Australia and the Indian Ocean as far as southeastern Africa. Accumulating the maximum CAMS total column SO_2 analysis values between 16 and 22 January reveals the large-scale extent of the plume transport across the South Pacific and Indian Ocean. In addition to SO_2, CAMS also provides information on sulphate aerosol, which can be formed chemically from SO_2. It monitored sulphate aerosol in the troposphere during its transport and found a clear signal in aerosol optical depth following the SO_2 transport across the Indian Ocean, where it was also detected in ground-based observations from the NASA Aerosol Robotic Network (AERONET) site in La Reunion.

Further impacts of the eruption were



Sulphur dioxide analysis. Maximum values of CAMS total column sulphur dioxide analyses between 16 and 22 January 2022, revealing long-range transport of the Hunga-Tonga plume following the eruption. The location of the volcano is marked by a grey triangle.

apparent in other observations used for NWP at ECMWF. These included temperature channels from microwave and infrared satellite observations. Perturbations to these channels were clearly detected in the first-guess departures when assimilated in the IFS (see www.ecmwf.int/en/about/media-centre/news/2022/hunga-tonga-eruption-seen-ecmwf).

The Hunga-Tonga eruption was a unique event both in terms of its destructive nature to Tonga and surrounding islands and in the way its impacts were observed by a large proportion of the global observing system. While some of these observations were indirect, the measurements related to SO_2 and atmospheric aerosols provided valuable information to understand the larger-scale impacts on the atmosphere and how they subsequently evolved.

An open-source Integrated Forecasting System

Michael Sleigh, Willem Deconinck, Michael Lange, Olivier Marsden, Balthasar Reuter

Parts of ECMWF's Integrated Forecasting System (IFS) are becoming open source, and the merits of moving the full IFS to open source in the future will be reviewed in consultation with Member States.

Currently, a distinction in licensing approach is made between the source code of the IFS and other ECMWF codes. Generally, non-IFS software is available under an open-source licence (Apache-2), while the approach to the IFS has been more restrictive. The IFS source is not publicly available, accessible only by ECMWF and its Member and Co-operating States. An 'open' version of the IFS does exist. It is known as OpenIFS (see ECMWF Newsletter No. 170) and is available to institutions for meteorological research. However, this is not fully open source and using it requires a bespoke licence.

In the June 2020 session of ECMWF's Council, options for making all or parts of the IFS open source were presented, along with a recommendation to allow carefully selected parts of the IFS to be released under an Apache-2 licence. The argument for open source for non-IFS code, that the benefits outweigh the risks, also applies to at least some parts of the IFS. Accordingly, it was agreed that the open-source approach should be extended to selected parts of the current IFS and to other developments envisaged to be part of the future IFS.

Aims

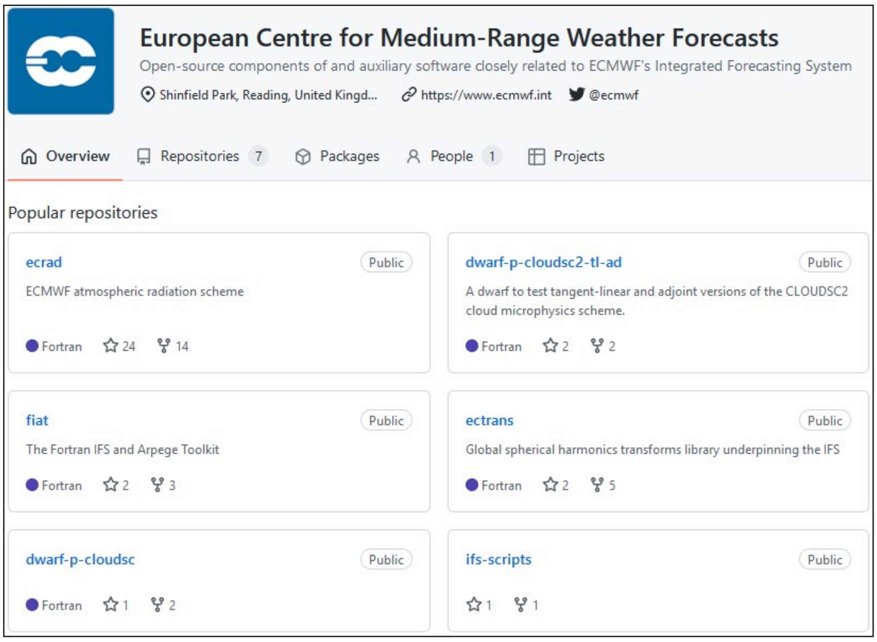
The aim is primarily enhanced collaboration. Removing restrictions on redistribution could make working with ECMWF more attractive to collaborators who wish to work with their partners. In some instances, further value can be provided through those wider networks. Additionally, contributing to open-source codes may be more attractive to academic partners.

A second purpose is efficiency. The present mixture of bespoke licences and open-source is relatively complex and ad-hoc, with significant time spent devising case-by-case solutions. A secondary consideration is that some journals require open access to codes used. So far, workarounds have been found (typically by providing code to editors/referees, for the purposes of the review), but this is time-consuming.

Furthermore, collaboration on scalability of the IFS with external organisations has been difficult. The OpenIFS licence allows only for meteorological research, not computer science research, and the version of the IFS used in the procurement of high-performance computing facilities is licensed only for benchmarking, not research. A third reason for considering open source is therefore to further position ECMWF and its Member States at the centre of international efforts on scalability and emerging high-performance computing architectures, by encouraging work on the IFS by computational science experts in academia and vendors.

Current availability

A GitHub space has been created to host open-source IFS components: https://github.com/ecmwf-ifs (see the image). This is distinct from the main ECMWF GitHub space (https://github.com/ecmwf), to signify a difference in purpose and support. The main space contains supported packages provided for the benefit of the community; the IFS space contains code released primarily to support pre-existing collaborations. While available to anyone, code in the IFS space is not generally supported.



GitHub space for elements of the IFS. The space contains code released primarily to support pre-existing collaborations and is not generally supported.

ecRad: The first component to become available was the ecRad radiation package. This was previously available under a bespoke licence but is now freely available under Apache-2.

ecTrans: The parallel spectral transforms from the IFS have been extracted and adapted in a standalone form useful to collaborators.

FIAT: A subset of IFS auxiliary routines required by multiple other packages has been released as FIAT (Fortran IFS and Arpège Toolkit). It includes routines used in the IFS for tracing, timing, controlling precision, and parallel communication.

CLOUDSC: A standalone version of the cloud scheme from the IFS. It was extracted in the EU-funded ESCAPE project (2015–2018) and was previously available under an ESCAPE licence.

CLOUDSC2: A new, simplified cloud microphysics scheme, including code to test the tangent-linear and adjoint versions of the scheme. Its purpose is to explore the impact of compiler optimisations and rounding behaviour on the symmetry of tangent-linear and adjoint solutions.

ecBundle: The bundle management tool used to build the IFS and other apps. It downloads code including dependencies and allows architecture-specific configuration for builds.

The future

Further components agreed to become open source soon are:

ecLand: This is the standalone land-surface scheme in the IFS, key to ongoing and future external collaborations, such as the addition of CaMa-Flood for hydrology modelling and EU-funded projects such as CoCO2, CONFESS and NextGEMS. Collaborations target developments on vegetation and photosynthesis modelling, urban tiles, snow and soil hydrology, and tight snow–ocean–sea-ice coupling.

ecWAM: This is the standalone wave model in the IFS, which will in future be even more tightly coupled to the IFS atmosphere, adopting the same grid. A crucial forthcoming activity is the GPU adaptation of ecWAM.

In addition to making components of the IFS open source, it was agreed at Council that ECMWF would also encourage further reviews, in consultation with Member States, of the merits of moving the full IFS to open source. It was noted that extending the approach to the whole IFS could have some significant advantages for collaboration and efficiency. Discussions are expected to begin in 2022.

From the Scalability Programme to Destination Earth

Peter Bauer, Tiago Quintino, Nils Wedi

This article recalls the origins of ECMWF's Scalability Programme eight years ago and how it helped to prepare ECMWF for the EU-funded Destination Earth initiative, which emerged through a considerable effort from some of the leading scientists in the field of weather and climate prediction and computational science. The Scalability Programme was designed to adapt weather prediction codes to emerging computing paradigms, and Destination Earth is an initiative to develop a highly accurate digital twin of our planet. Both initiatives illustrate how fruitful international collaboration can be, but they also highlight the challenges for devising and implementing large and ambitious programmes supporting the digital revolution of Earth system science.

The scalability challenge

ECMWF launched its Scalability Programme in 2014 as a result of the realisation that the efficiency of our substantial codes and complex workflows would not be future-proof in view of new, emerging computing paradigms. In particular, CPU processor performance was being capped to reduce power consumption. At the same time, substantial investments in software were needed so that emerging, alternative processor technologies like GPUs could be explored. GPUs have been around in high-performance computing (HPC) since 2006, but they presented serious code adaptation challenges that limited their use as a general-purpose computing device and delayed their wider uptake in operational weather and climate prediction. A notable exception was MeteoSwiss, which invested in a substantial, manual GPU code rewrite early and operationalised its limited-area prediction system on CPUs and GPUs in 2016.

It also became clear that enhanced computing requires enhanced data handling capabilities, as big computing creates big data. The classical approach of storing all model output on tapes and performing frequent read and write operations was going to change radically in the future. The data handling challenge appeared to be more critical at the model output than at the observational data input stage as model output increases at least by an order of magnitude when resolution is doubled.

Advances in research and operational prediction lead to a doubling of horizontal resolution about every eight years. Upgrades in vertical resolution and the use of ensembles in assimilation and forecasts add to the multiplication of the computing and data burden. With no sign of such demands reaching saturation, there was increased pressure to make a dedicated investment in scalability.

In the past, continuous efforts were made to exploit shared and distributed processor memory in ECMWF's Integrated Forecasting System (IFS). However, a rethink of algorithmic choices and computational efficiency became necessary because of a number of developments: the complex setup of semi-implicit spectral and grid-point calculations; the semi-Lagrangian advective transport and its necessary data communication; and the coupling to increasingly complex Earth-system-component models for waves, ocean, sea ice and land, based on different grids, solvers and computational patterns. Any improvement also needed to be sustainable and thus portable to emerging and future computing architectures without repeatedly redesigning models, algorithms and work- and dataflows.

Scalability Programme – the research phase

The Scalability Programme was launched as a concerted effort across ECMWF and its Member States. Contrary to most projects run at the same time at most weather services and climate prediction centres, the ECMWF programme targeted both efficiency and sustainability of the entire work- and dataflow.

Initially, the programme was formulated around several projects focusing on observational data ingestion and pre-processing, data assimilation and the forecast model, model output data handling and product generation.

Finding resources

Once initiated, the programme needed resources. Our Member States were very supportive as performance and technology concerns were widely shared across the weather and climate community. The ECMWF Council agreed to add five staff members in 2014. The first generation of scalability staff came mostly from diverse, non-meteorological backgrounds.

doi: 10.21957/pb2vnp59ks

This delivered multi-disciplinary innovation from other fields that also rely on strong computational science expertise, such as acoustics, aerospace and fluid dynamics. It became a template that has worked very successfully ever since.

Another pillar of collaboration was created through externally funded projects supported by the European Commission's Future and Emerging Technologies for HPC (FET-HPC) programme. This allowed us to draw in the expertise of likeminded weather prediction centres, academia like the nearby University of Oxford, HPC centres, and computer technology providers like NVIDIA and Atos. It also helped to create a new ecosystem where this expertise could accelerate progress in a concerted way and create community solutions that benefited more than one centre. ECMWF's membership in the European Technology Platform for HPC (ETP4HPC) allowed suitable partners to be found and requirements to be defined for the ETP4HPC strategic research agenda, which stimulated new ideas for the European Commission's funding programmes.

Following the broad scope of the Scalability Programme, the first generation of these European projects, called ESCAPE and NextGenIO, aimed to revisit basic numerical methods through so-called weather and climate dwarfs and adapting them to GPUs. They also explored different levels of the memory hierarchy, where new technologies offered alternative programming solutions and speed-ups to perform costly calculations, such as model output post-processing on the fly without the need for accessing spinning disks. Exploring processor-focused parallelism and memory-stack-focused task management together produced numerous options for efficiency gains. ECMWF partnered with several Member States, universities and leading vendors, such as NVIDIA, Atos, Cray, Fujitsu and Intel, to facilitate co-design with the latest available technology.

Since then, the dwarf concept has reached wide acceptance in the community. This is because it breaks down the overall complexity of full models but still represents realistic model components with intensive and diverse computational patterns that can be tested at scale. Always considering compute tasks and dataflow together created much more realistic solutions for real-life prediction systems.

ECMWF also participated in formulating the programme for the ESiWACE Centre of Excellence, which created a new hub for developments serving both weather and climate prediction, thus joining these communities for seeking common solutions to identical challenges. These external activities were paired with internal projects to align all efforts towards fulfilling ECMWF's operational needs.

Research focus

The next generation of projects continued and intensified the work on these topics, and they further extended partnerships. Many projects were formulated around new and emerging, general-purpose technology where ECMWF contributed one of several applications (MAESTRO, LEXIS, ACROSS, DEEP-SEA, IO-SEA, EUPEX, HiDALGO). A few projects had weather and climate prediction itself as the focus. A variety of new methods and technologies were trialed and assessed together (ESCAPE-2, ESiWACE-2, MAELSTROM). So far, ECMWF has been involved in 15 such projects drawing in over 10 million euros for developments at ECMWF since 2015 (Figure 1).

Another cornerstone has been the testing of the evolving IFS at scale on some of the largest HPC infrastructures in the world. While these tests were started before the Scalability Programme existed, they were carried out more frequently and at larger scale through the programme and also took in our scalability developments as they evolved. For example, we used what were then Europe's fastest supercomputer, Piz Daint at the Swiss National Supercomputing Centre (CSCS, June 2017, top500), and the world's fastest supercomputer, Summit (June 2018 to November 2019, top500). More recently, we carried out work on Europe's latest, fastest machine, the JUWELS Booster (November 2021, top500), and on the world's fastest machine, Fugaku (November 2021, top500). Access was granted through several competitive US INCITE awards and Europe's PRACE programme, but also through bilateral agreements with e.g. Japan's research institution RIKEN and the Swiss CSCS.

Over time, the complexity of these tests increased from shorter model integrations to seasonal and ensemble simulations at 1 km spatial resolution, while solving associated data challenges at these scales at the same time. The trials have been crucial for understanding new architectures and the remote deployment of workflows. They also helped to understand the limits of scalability, and they created unique datasets for gauging what science challenges and opportunities lie ahead, also in support of machine learning.

Scalability Programme – the implementation phase

With the completion of the first, research-oriented phase, ECMWF took stock of the results obtained so far, assessed the options for further development, and identified a roadmap for implementing research into operations. Some of the highlights include:

- establishing the quantitative limits for business-as-usual performance speed-ups, i.e. the baseline

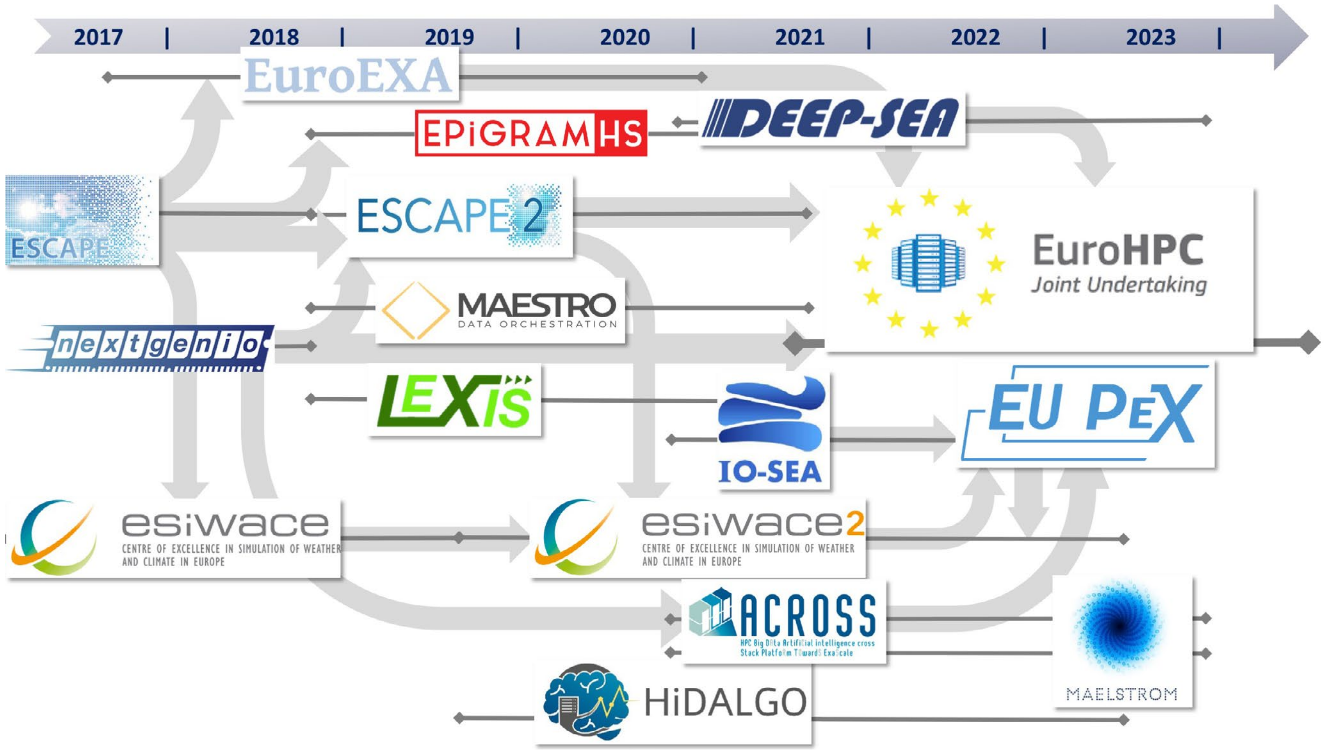


FIGURE 1 Many Scalability Programme projects with ECMWF involvement have been funded by the European Commission. The projects support basic developments for numerical methods and algorithms, adaptation to different hardware architectures, extreme-scale data handling, and community-serving centres of excellence. This created numerous collaboration opportunities with ECMWF Member States, academia, HPC centres and digital technology vendors. For more details, consult *https://www.ecmwf.int/en/research/projects*.

against which intrusive changes need to be compared

- developing the concept of dwarfs, tested on different processor technologies and optimised to the extreme
- preparing alternative formulations of model components, including the IFS-Finite Volume Model (FVM) dynamical core, which would overcome fundamental limitations of the spectral core
- developing and testing the new domain-specific language (DSL) concept for separating legible science from highly optimised code layers targeting different processor types, and automated source-to-source code transformation tools (Loki; GridTools for Python, GT4PY-FVM)
- first successful adaptation of dwarfs to more exotic dataflow processors, such as field-programmable gate arrays (FPGAs)
- testing and implementing mixed-precision developments (atmosphere and ocean models), which become increasingly effective due to machine-learning-targeted processor developments by industry
- developing ECMWF's new data structure library Atlas, which greatly facilitates operations on diverse grids and meshes, also for coupling different model components
- implementing the object-based datastore for workflow acceleration and product generation, ECMWF's Fields Database (FDB5), into operations
- full demonstration of model output post-processing for a 1 km ensemble based on FDB5, using the latest high-bandwith, non-volatile memory extension technology
- developing the new IO-server supporting all Earth-system model data (MultIO)
- implementing a new, data-driven simulator for realistic workflows (Kronos), successfully used in ECMWF's recent HPC procurement.

The Scalability Programme also spun off a new ECMWF activity on machine learning that has established a roadmap for applications across the entire prediction workflow. This activity has created a new level of partnerships with Member States, academia and vendors and served as a template for similar activities run by other centres and agencies.

The rather wide scope of projects, the demonstration of successful developments, and the new levels of collaboration also planted the seeds for the ECMWF-

Atos Center of Excellence in HPC, AI and Quantum computing for Weather & Climate. The centre of excellence has selected performance-portable codes and machine learning as the main topics for future co-development.

Road to operations

These outcomes were used to focus the second phase of the programme on the two main challenges for ECMWF's forecasting system: performance-portable codes, and data-centric workflows including distributed computing and data access models.

To turn the first task into operations, the new Hybrid2024 project was created. It aims to produce a hybrid CPU-GPU version of the IFS that is suitable for the post-Atos HPC procurement with a readiness date in 2024. Reduced precision is already operational at ECMWF today and has facilitated an increase in vertical resolution for the ensemble without requiring a new supercomputer. The OOPS data assimilation framework is entering operations in 2023. It provides a high-level control structure for the IFS, separates concerns of data assimilation and model, and makes the IFS more modular in preparation for Hybrid2024. Modularity and Member State support are also enshrined through Atlas. It is an open-source community library that serves as a common foundation to develop new algorithms, serves as possible data structures for DSLs, enhances Member State collaboration and interoperability between Earth-system model components, and is already used by a growing number of Member States and external partners. The Atlas developments helped to inspire ECMWF's operational triangular-cubic-octahedral (TCo) grid, and to support the rapid development of the IFS-FVM dynamical core.

The second focus is being established without creating a new project but by defining individual implementation targets for the key data-centric workflow components. These are FDB5 (already operational); the parallel I/O-server MultIO; the transition of the observational database to an FDB-type object store; and the connectivity to external, cloud-based infrastructures pioneered by the European Weather Cloud (EWC).

Increasingly, distributed computing and data handling are becoming necessary. This would ensure that even large model ensembles could be run externally (e.g. through containerised workflows) with dedicated cloud computing infrastructures. Data analysis would be large-scale too, therefore requiring dedicated computing resources close to the data and providing seamless access for users. This is part of ECMWF's future cloud computing strategy and includes the further development of the EWC and its convergence with the HPC infrastructure.

In addition, the second phase of the programme continues to invest in basic research on new numerical methods (finite volume and discontinuous Galerkin methods). New processor generations including non-x86, or non-GPU types like Fujitsu's A64FX, and emerging low-power processors of the European processor initiative (EPI) will likely require reduced precision by default and may be more suited to execution models based on machine learning. Similar to the emergence of GPUs, these additional technology options also create challenges, and early access to prototypes combined with innovative, computer-science-driven thinking continues to be one of the leading driving forces for the Scalability Programme's next phase.

The Scalability Programme involved many individuals at ECMWF and greatly benefited from our collaboration with Member States, academia, HPC centres and vendors, which also created the foundation for the partnerships envisioned for Destination Earth.

Destination Earth and its origins

Destination Earth (DestinE) is funded by the European Commission's new Digital Europe programme. It was signed by DG-CNECT on behalf of the Commission and the European Space Agency (ESA), ECMWF and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) as entrusted entities on 15 December 2021. The programme supports the European Green Deal by delivering a new type of information system based on so-called digital twins of Earth. ECMWF produces the digital twin infrastructure and digital twins on weather and geophysical hazard-induced extremes and climate change adaptation, ESA contributes the core service platform, and EUMETSAT the data repository, called data lake. The first phase of the programme is 2.5 years long. It focuses on developing and demonstrating the functionality and novelty of different infrastructure and software components contributing to the wider DestinE digital environment. It will be followed by future phases in which the scope and operational level will be increased and used in a wide range of services.

Consolidating science and computing

DestinE is rooted in several initiatives, all of which ECMWF was involved in, sometimes in a leading way. The ground was laid in 2008 at the World Modelling Summit. T. Palmer (ECMWF at the time) and J. Shukla (George Mason University) were the driving forces behind the Summit, which was co-organised by Martin Miller (ECMWF). The event focused on climate prediction and concluded that a dedicated effort was needed to close apparent gaps in climate models, merge efforts across weather and climate communities and invest in dedicated computing resources to accelerate progress. The Summit was held at ECMWF, co-organised by the World Climate Research Programme (WCRP), the World Weather Research Programme (WWRP), and the International Geosphere-Biosphere Programme (IGBP). DestinE-type targets, such as 'kilometer-scale modelling' and 'regional adaptation and decision making', were already included in the Summit's report in 2009.

In the years following this event, the recommendations were turned into a proposal to create a new, centralised but international institution. This would create the critical mass for producing a much-required breakthrough for operationalising climate science production around a central piece of technological infrastructure, including dedicated HPC resources. It took more than five years and an opportunity created by the European Commission to provide this concept with a more solid underpinning.

The next step was an international workshop at Chicheley Hall in the UK in 2016, which gathered 21 of Europe's leading climate scientists to revise the original Summit's concept and incorporate the latest developments in Earth system science, numerical modelling and computing. The workshop was conceived by T. Palmer (then University of Oxford) and B. Stevens (Max Planck Society). The outcome was called the European Programme on Extreme Computing and Climate (EPECC). EPECC gave our efforts a sharper scientific focus on the topic of extremes and their origins, the recognition that resolving small scales would be essential for obtaining large-scale predictive skill, and the realisation that refining parametrizations would not overcome key model deficiencies.

EPECC was led by T. Palmer and was submitted in response to the European Commission's consultation on new ideas for so-called Flagship initiatives: large and ambitious research programmes aiming for moon-shot type targets and equipped with 1 billion euros over ten years. The consultation phase was followed by a call for preparatory projects for such Flagships. If successful, they would receive 1 million euros for one year to prepare the fully-fledged Flagship concept.

The preparatory project was coordinated by ECMWF because of our leading role in numerical weather prediction and our substantial investments in scalability, further emphasizing the synergy between Earth system and computational science. The fact that ECMWF is a Member State organisation that represents the successful process of pooling financial and intellectual resources in a single effort also helped, as EPECC was aiming to repeat this partnership concept in a different form. The proposal included a partnership with 18 institutions from weather services in our Member States, HPC centres, national research and public-serving institutions, and university labs.

Flagships received substantial attention, partly due to their high budget and visibility, and Earth-system and environmental change topics were likely to appear in several, parallel submissions. This is why EPECC was eventually merged with two other efforts, one led by UK Research and Innovation (UKRI) and the Helmholtz Association in Germany, and the other led by the University of Helsinki in Finland. The resulting project was called ExtremeEarth (*https://extremeearth.eu/*) and had expanded from weather and climate to geophysical extremes. It also contained a stronger inclusion of observational infrastructures through these partnerships. However, it retained its focus on very high-resolution simulations of the fluid and solid Earth; advanced simulation–observation data fusion, enabling digital technologies like extreme-scale computing and data handling; and the creation of an ExtremeEarth Science Cloud, which was an important product of the merger process. The latter laid the foundation for the digital twin concept and aimed at a similar functionality as DestinE today. ExtremeEarth was supported by many organisations and scientists in Europe and received over 120 endorsements from organisations worldwide. Outside ECMWF, the core writing team comprised B. Stevens, W. Hazeleger (escience Centre, now Utrecht University), T. Jung (Helmholtz Association), T. Schulthess (CSCS), D. Giardini (ETH Zurich), P. Papale (INGV), J. Trampert (Utrecht University) and T. Palmer, and many others contributed.

ExtremeEarth passed the first round of reviews, coming second out of 33 proposals. One year later, however, the entire Flagship programme was terminated as Flagships were deemed ineffective tools for the new Horizon Europe programme. This meant a new programmatic home was needed.

Shaping Destination Earth

It took more than two years to disassemble ExtremeEarth and reassemble DestinE so that the original spirit was retained, but the changing boundary conditions were taken into account as well. An example of a changing boundary condition was that Brexit happened and the UK was no longer an EU member state and therefore not associated with the Digital Europe Programme, from which DestinE was funded. The European Commission also proposed that ESA and EUMETSAT partner with ECMWF so that their combined experience in running large programmes could be brought together. Another boundary condition was that Flagships as a sole instrument were discontinued and DestinE needed to be funded by a new programme that did not yet exist.

The thematic hook was given by the new European Green Deal announced in December 2019, for which DestinE would provide a unique information system in support of decision-making. Soon after, the European Commission also published a new digital strategy. This became the basis for DestinE's ambition to implement a highly flexible digital infrastructure hosting advanced simulations that are informed by observations. This infrastructure became labelled as the 'digital twin of Earth'. It took some time to exactly capture what the definition of such a digital twin is, and how it would be different from existing Earth system simulation and data assimilation systems that many meteorological services and the EU's Copernicus Earth observation programme already operate. However, the components of ExtremeEarth, in particular the ExtremeEarth Science Cloud, had paved the way for this definition.

Digital twins have a history in engineering, where digital models of a factory or aircraft help to design assets, but also help to optimise their production and enhance performance and reliability during operation. There is a clear distinction between a digital simulation, a digital shadow and a digital twin. The simulation only casts the real asset in a digital model, while the digital shadow uses real-world observations to inform the model. The twin goes one step further as the model informs actions in the real world. Thus the asset is modified as a result of decisions made based on the model, and the modifications become part of the model.

In our domain, weather prediction systems are already digital shadows as we use numerical models supported by hundreds of millions of observations to constrain the simulations and create analyses serving as initial conditions for forecasts. Making the step to a digital twin requires three major upgrades:

1. Enhancing the simulation and observation capabilities, such that the model becomes much more realistic and therefore creates a better global system providing reliable information at local scales where impacts are felt
2. Including and ultimately interacting with models and data from sectors that matter for society, namely food, water, energy, health and risk management
3. Creating all digital elements for an information system that allows intervention, such that users can create information that is optimized for their specific purpose, add their own data, build new digital components, and deploy them for decision-making.

(1) was the core message of EPECC while (2) and (3) emerged most strongly through ExtremeEarth. All predecessor projects made a strong point about extreme-scale computing and data handling being critical for success. Going further, ExtremeEarth proposed so-called extreme-scale laboratories as research melting pots where the computing and data challenges would be solved across disciplines.

DestinE replaced this by the notion of the digital twin engine, which is the extreme-scale technology heart of any Earth system digital twin. In the digital twin engine, different models and twins share software and

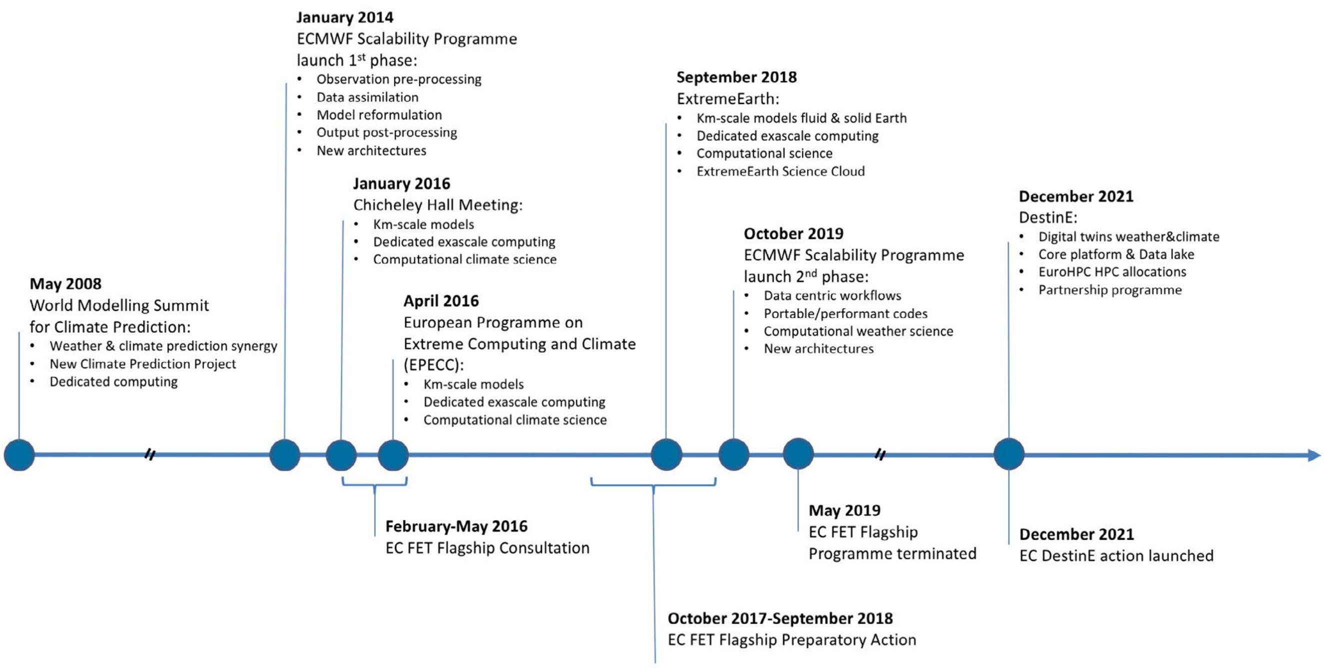


FIGURE 2 Timeline of events leading to DestinE. It moves from first concepts of a dedicated programme for climate prediction and extreme-scale computing and the foundation of the Scalability Programme to efforts to create a European-level funding framework for joining weather, climate and computational science within DestinE.

infrastructure (e.g. a platform or software as a service), providing portable solutions between architectures and permitting scaling from small to very large applications. The engine supports interactive access to the full twin data stream in real time, where access window, modes of use and applications can be configured as required.

As can be easily seen, all this closely links to the development goals of the Scalability Programme. This link brings a well-established engineering approach into Earth system science to support how society adapts to change and mitigates the consequences of change based on the best available science empowered by the best available technology. Figure 2 provides an overview of the timeline of the Scalability Project and Destination Earth.

The first phase

The three main components of DestinE are the digital twin framework, the core service platform, and the data lake. They will be implemented by ECMWF, ESA and EUMETSAT, respectively. The first phase, December 2021 to June 2024, is dedicated to developing the individual digital technology components and demonstrating their individual functionality, but also how they work together as a system of systems.

The digital twin framework comprises the digital twin engine, which is the simulation and data fusion system. It makes it possible to run very advanced models informed by more and better observations, and it increasingly drives more applications across more impact sectors through the synergy of science–technology capabilities (see Figure 3). The initial focus on weather-induced extremes and climate change adaptation will be extended towards other themes later. The core service platform will be the main hub that users interface with and through which they gain access to all data and tools that DestinE will facilitate. The data lake will be a repository providing access to digital twin data. It will also give access to a large product diversity that DestinE will generate and accumulate from other sources, such as Copernicus.

The European Commission has allocated a total of 150 million euros to the first phase, with individual shares of 60, 55 and 35 million euros for ECMWF, ESA and EUMETSAT, respectively. DestinE will therefore benefit the Member States of the three organisations involved in DestinE in several ways. First, all three entities are intergovernmental organisations and have been cooperating with their Member States for decades. This will ensure that DestinE will produce direct benefits that many countries can share in terms of data, software and science by default. Second, the procurements offer a wide range of funded

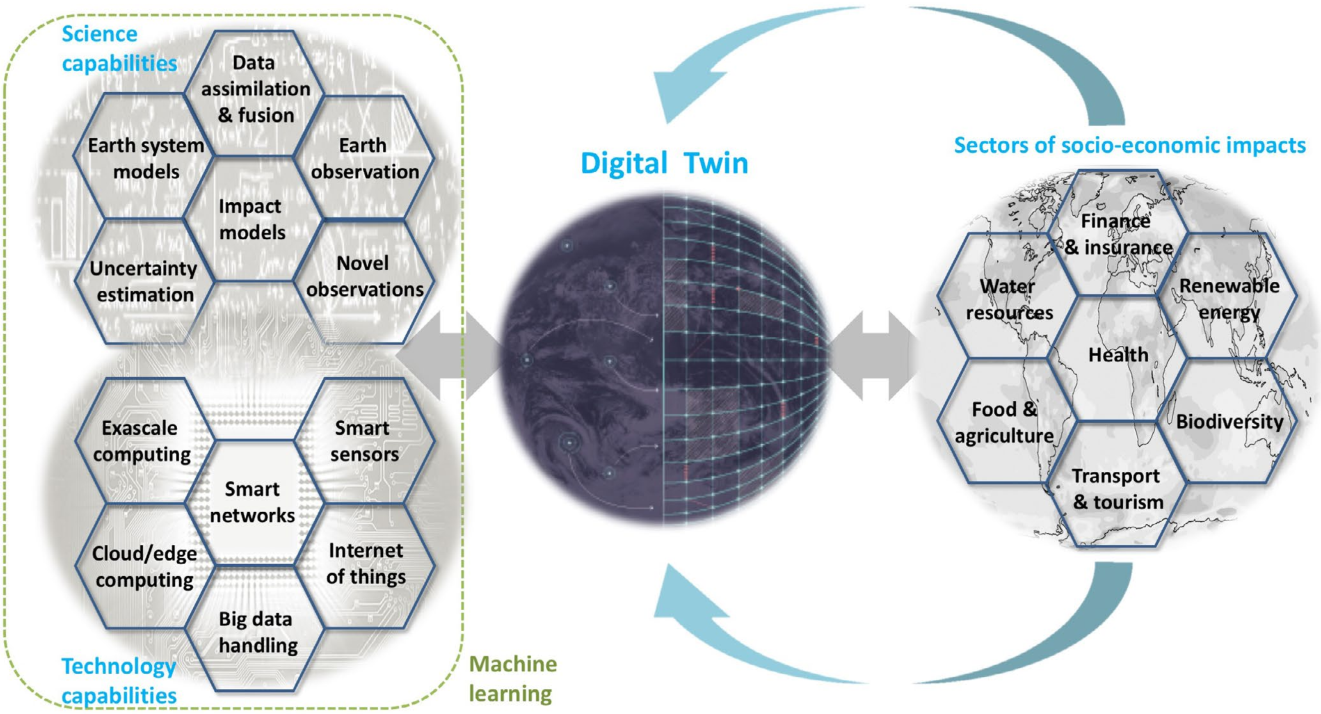


FIGURE 3 Digital twins are a tool to enable sectors of socio-economic importance to gain access to the best quality of data and to create tools to extract application-specific information. A digital twin builds on the convergence of leading science and technology capabilities based on simulations and observations through exploiting the entire range of digital technology. It is supported by machine-learning methodologies across all components.

collaborations for creating the DestinE digital technology capabilities, which Member States can use themselves for their own benefit. Third, DestinE will create a substantial partnership programme that ensures that its aims and objectives will co-evolve with existing service providers, such as Copernicus and national meteorological and hydrological services. This is further strengthened by new funding opportunities at European (Horizon Europe) and national levels, which will support DestinE with basic research and infrastructures so that a continuous innovation cycle is created.

DestinE aims to establish its role as a unique accelerator and capability provider that sits at the interface between science, applications and technology. It feeds innovation into services, and it ingests specialist research, development and application partnerships. ECMWF's expertise in Earth system modelling, the assimilation of vast amounts of diverse observational data into models, and its leading role in Copernicus service delivery, combined with its decade-long investments in extreme-scale computing, data handling and machine learning through the Scalability Programme, have therefore created a unique foundation to provide a new level of monitoring and prediction capabilities.

The Scalability Programme has positioned ECMWF to be a leader in the digital revolution sweeping through European climate and weather science, and in so doing it gives ECMWF and its Member States the opportunity to shape this revolution.

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Developing an all-surface capability for all-sky microwave radiances

Alan Geer, Katrin Lonitz, David Duncan, Niels Bormann

In the ECMWF Strategy 2021–2030 we aim to move to an 'all-sky all-surface' assimilation of satellite observations. Cycle 48r1 of ECMWF's Integrated Forecasting System (IFS) is planned to go operational in early 2023, and it will include extensive changes to make better 'all-surface' use of satellite microwave observations.

The upgrades target surface-sensitive microwave channels, for which a lot of data has previously been screened out due to surface types that are harder to simulate. These surface types include land, snow, sea-ice, and mixtures of all surface types. In some channels, the new developments increase the number of observations being assimilated by around 30%, particularly in polar regions and over mixed scenes. The main forecast improvements are in northern high-latitude areas, showing the importance of trying to use more satellite data in these areas.

Main improvements

The Cycle 48r1 developments are just a step in the direction of a complete all-surface assimilation, but they help us preview what we will be working on over the coming decade. For example, in Cycle 48r1 we will be retrieving the sea-ice fraction from microwave observations for the first time in the IFS. It is not yet good enough to be assimilated in the sea-ice analysis, and initially it is intended only for quality control of the microwave observations. But there is clear potential for inferring more surface information directly from satellite radiances in coupled data assimilation.

One component of the package in Cycle 48r1 is the addition of surface-sensitive microwave imager channels over land surfaces. This is a first in global weather forecasting and it depends on having a well-developed 'all-sky' assimilation framework. This is because the main atmospheric information in surface-sensitive channels does not come from temperature or water vapour, but from cloud, rain and snow in the atmosphere. We can now use these observations to help correct forecast errors, such as displaced summertime convection over central Europe. However, the amount of information we can extract is limited by our ability to model the effect of land surfaces on satellite radiances, which is still difficult, particularly in snow-covered areas and deserts. Improvements to radiative transfer modelling for sea-ice, snow and land surfaces are critical to progressing the all-sky all-surface strategy.

Another issue that we begin to grapple with in Cycle 48r1 is the treatment of mixed surfaces. These have previously been considered too difficult to assimilate, leading to a loss of data over coastlines, islands and lakes. If we also include mixed ocean/sea-ice surfaces in the figures, then mixed scenes can easily comprise 20% of all microwave radiances, which is a significant loss.

Different surface types have very different effects on the observed radiation, so it is important to know the exact fraction of each surface type in a mixed scene, and to model each surface type appropriately. This makes it more important to know the exact location and shape of the satellite field of view, which can often be much broader than a single IFS grid box. When targeting the atmosphere, it is possible to get away with more approximate treatments. Now that we are hoping to target surface variables, it pushes us to represent the satellite field of view more exactly. All these areas will be important themes of development over the next few years.

More observations in difficult areas

Currently, the all-sky microwave framework is used to assimilate around 17 different sensors and satellites. This includes conical scanners (known as microwave imagers) mainly targeting lower-tropospheric water vapour, cloud and precipitation, and microwave sounders, targeting the humidity or temperature profile, but also sensitive to cloud and precipitation. Together these observations represent around 30% of all observational impact on the short-range forecast.

All these sensors have channels that are sensitive to the surface, but they are only partly utilised or sometimes completely rejected. The impact of the ice-free ocean surface on microwave radiances is relatively well modelled, so coverage over the tropical and midlatitude oceans is mostly complete. By contrast, many observations must be rejected over land and sea-ice areas due to our imperfect physical knowledge of these surface types.

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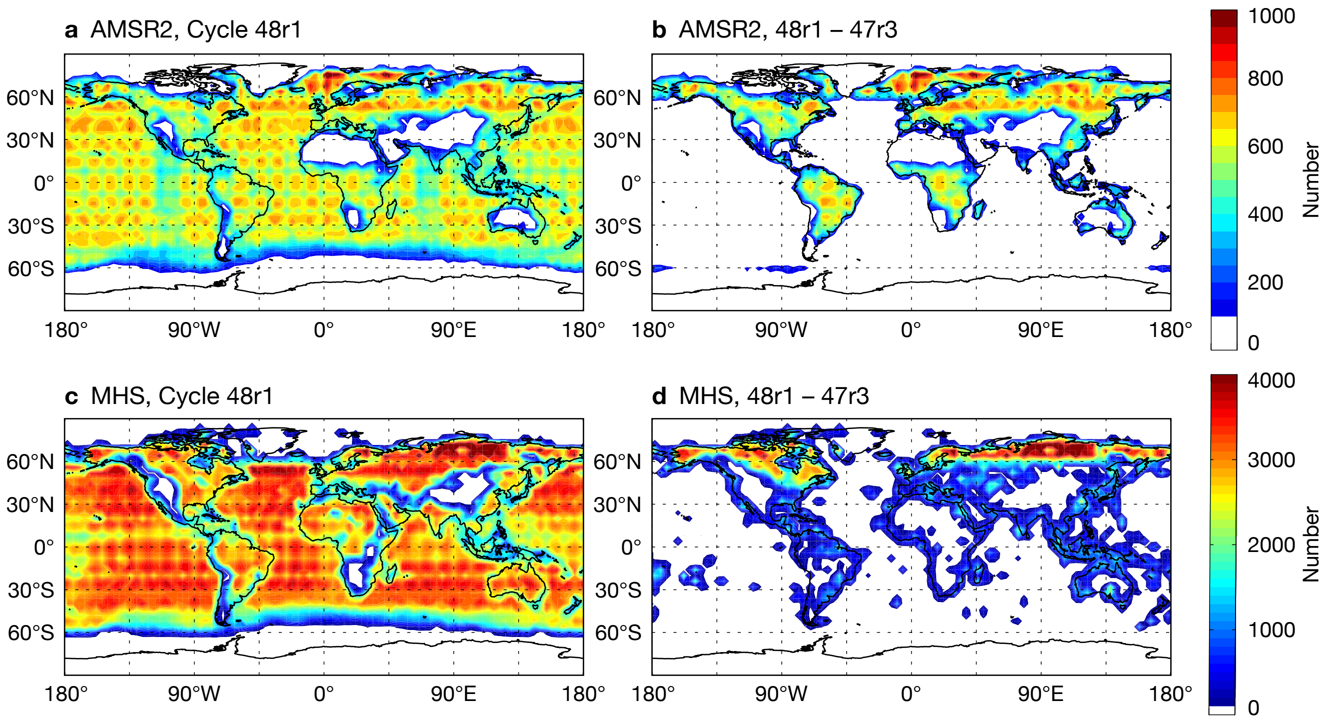

FIGURE 1 The charts show (a) the expected number of observations to be assimilated in Cycle 48r1 from the Advanced Microwave Scanning Radiometer – 2 (AMSR2) in channel 12 (89 GHz, v-polarisation) from one satellite, (b) the increase compared to 47r3, (c) the expected number of observations to be assimilated in Cycle 48r1 from the Microwave Humidity Sounder (MHS) channel 5 (183±7 GHz) from four satellites, and (d) the increase compared to 47r3. The experiments cover July 2020.

Figure 1 illustrates expected improvements in observational coverage in Cycle 48r1, based on experiments for July 2020. For microwave imager channels like the one shown in Figure 1a,b, observations are added over ice-free polar oceans thanks to new sea-ice retrieval. This enables us to accurately screen out any observations that contain sea-ice, where previously we had to exclude all polar ocean areas as a precaution. Observations are also used over most land surfaces for the first time. This is thanks to a new technique for extrapolating the surface radiative properties across frequencies, based on retrievals at lower frequencies that are less sensitive to cloud and precipitation. It is still too difficult to use observations in this channel over sea-ice, snow, desert or high-altitude surfaces, so there are still some big gaps to fill.

Figure 1c,d shows the new coverage, along with changes, in a microwave humidity sounding channel that has benefited from some of the other components of the 48r1 package. There are more observations over land at high latitudes, thanks to the removal of a quality control check that discarded land observations poleward of 60 degrees. Also evident are more observations around coastlines, islands and lake areas, where the improved treatment of mixed surfaces has also allowed ‘coastal’ scenes to be used for the first time.

Benefits to forecasts

Figure 2 shows the change in wind forecast error coming from the all-sky all-surface upgrade in Cycle 48r1. Blue areas indicate small but often significant improvements in forecasts over high northern latitudes. These results were based on the experiment’s own analysis as the reference, but an observational reference confirms the improved forecasts. For example, background forecasts are around 0.5% better when compared to radiosonde temperature, moisture and wind profiles in Arctic areas (defined as poleward of 60 degrees N, not shown). The recent APPLICATE project has also highlighted the importance of using more satellite observations in polar regions, especially in winter (see Sandu et al., 2021; Lawrence et al., 2019).

The improvements in Cycle 48r1 likely come from the additional observations over the Arctic Ocean and northern hemisphere land areas, including the many lakes, islands, and coastal scenes that were previously rejected. We were particularly interested to see if the additional microwave imager observations over land were responsible for part of the improvement.
As mentioned, these observations are mainly sensitive to cloud and precipitation over land, with less sensitivity to forecast variables such as wind and temperature. But experiments showed that these cloud and precipitation observations probably are contributing to the initial conditions of wind and temperature, too. This would be expected from the generalised tracer effect of 4D-Var data assimilation, which allows us to infer changes in humidity, winds, temperatures and surface

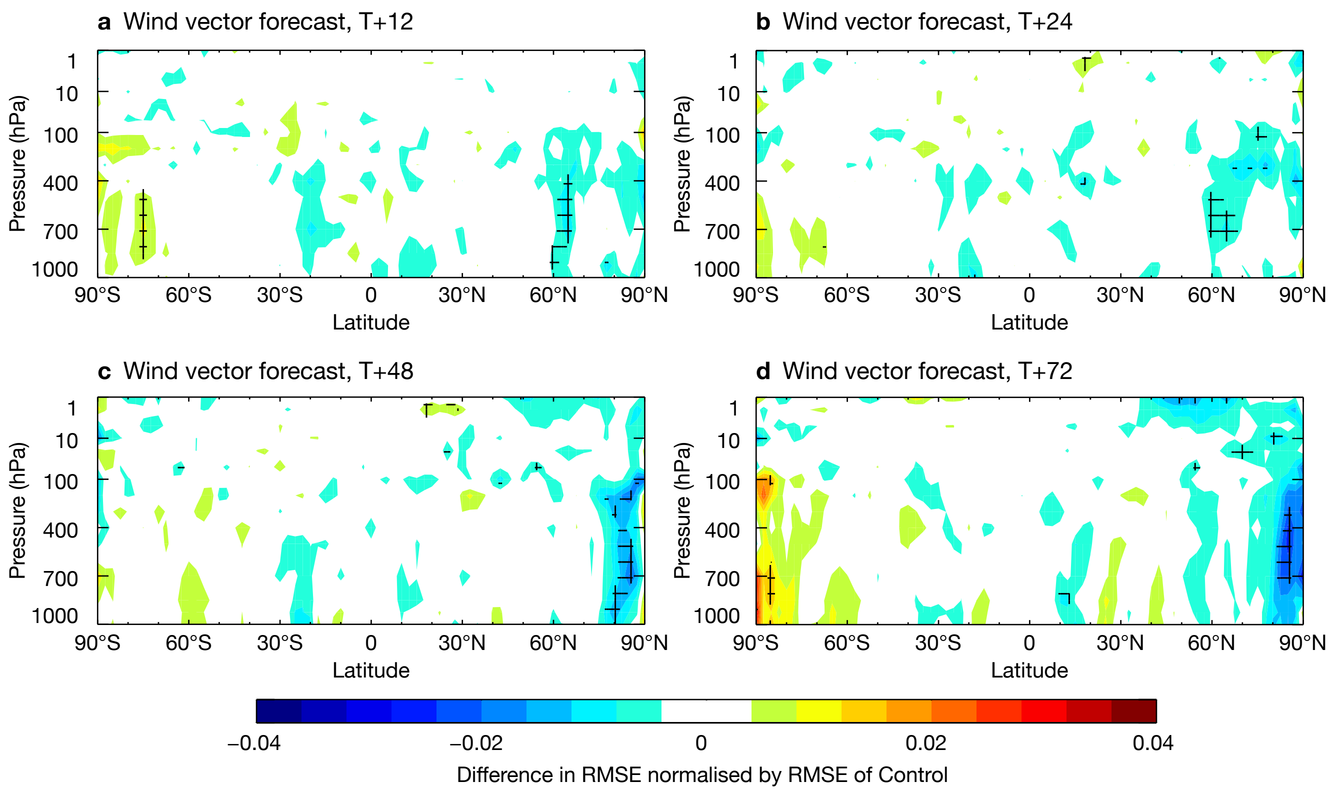

FIGURE 2 Normalised change in root-mean-square error (RMSE), in an experiment with the all-surface assimilation changes to be included in Cycle 48r1 compared to a control, of wind vector forecasts (a) 12 hours ahead, (b) 24 hours ahead, (c) 48 hours ahead, and (d) 72 hours ahead, verified against own analysis, and based on approximately six months of experimentation. Cross-hatched regions are statistically significant at 95%. Blue areas indicate a reduction in forecast error and hence an improvement in forecast quality. Note that much of the yellow (forecast degradation) areas are below the surface, which is around 700 hPa at the South Pole. This is a result of doing the verification on fixed pressure levels, which are just extrapolations below the surface in some areas.

pressure in order to better fit the observations of cloud and precipitation.

Inferring sea-ice fraction from microwave observations

The new sea-ice retrievals to be used in Cycle 48r1 are based on the 10 GHz channels available on some microwave imagers. These low-frequency channels are ideal for inferring the sea-ice fraction because there is a strong contrast in the brightness of the ocean surface and of the sea-ice. These channels have not been used in the IFS before because their atmospheric signal is relatively small. As we move towards all-surface assimilation, low frequency microwave channels are likely to play an increasing role, especially with upcoming sensors like the Copernicus Imaging Microwave Radiometer (CIMR), which will provide observations down to 1.4 GHz.

Figure 3 shows the quality of the initial 10 GHz sea-ice retrievals, compared to the sea-ice fraction that is computed by the OCEAN5 analysis. The overall ice extent is well captured by the new retrievals, but especially in the Arctic in this example, the sea-ice fraction is overestimated. For present purposes this is fine, since the retrieval is only aimed at identifying scenes that are contaminated by sea-ice for quality control of the atmosphere-targeted microwave observations. The retrievals give an instantaneous view of the sea-ice in the satellite's field of view, whereas the OCEAN5 analyses are based on observations that are up to 48 hours old. This means that the analysed sea-ice edge can be in error by up to around 100 km.

If we can find better ways of modelling the radiative properties of the sea-ice, it will be possible to retrieve a sea-ice fraction that might be accurate enough to try assimilating at ECMWF. There is the possibility of rapid progress in this area, which will be the focus of much work in the coming years.

Radio spectrum challenges

Cycle 48r1 will mark the first time that ECMWF directly assimilates radiances from surface-sensitive channels over land surfaces. These channels occupy small chunks of radio frequency that are protected from other radio emissions, such as 5G mobile telecommunications. However, there is constant pressure on the small amounts of radio spectrum that have been reserved for scientific purposes. Only recently, space agencies and science organisations

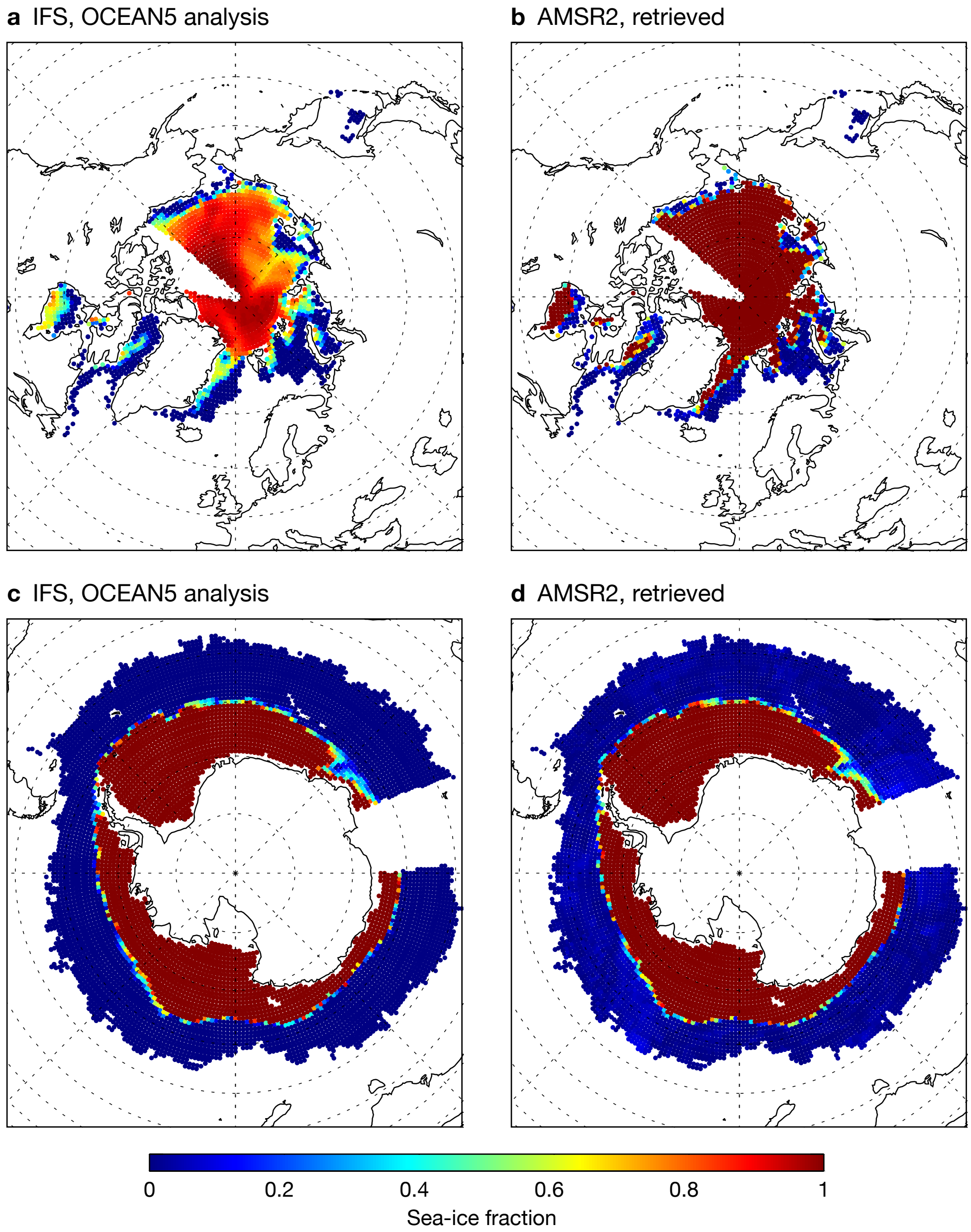

FIGURE 3 The charts show (a) sea-ice fraction in the IFS from the OCEAN5 analysis in the Arctic, (b) retrieved sea-ice fraction from AMSR2 channel 6 (10 GHz, h-polarisation) in the Arctic, (c) sea-ice fraction in the IFS from the OCEAN5 analysis in the Antarctic, and (d) retrieved sea-ice fraction from AMSR2 channel 6 (10 GHz, h-polarisation) in the Antarctic. The sea-ice fraction from the AMSR2 retrievals will be used in Cycle 48r1 for quality control of the observations. The comparison is made at observation locations in the 00 UTC analysis on 1 July 2019, and only for ocean observations with skin temperatures lower than 278 K. This explains the missing segments of data over the Arctic and the Antarctic, and the relatively small halo of ocean points around the identified sea-ice areas.

including ECMWF had to make the case for better protection of 24 GHz observations against unwanted emissions from 5G telecoms applications in neighbouring bands.

We know how much more information we can still extract from microwave observations over land surfaces, but to continue justifying these protected scientific bands, we will need hard evidence of their beneficial impacts on operational environmental forecasts. In some areas, we may be in a 'use it or lose it' situation as commercial demands on the radio spectrum continue to increase. Hence, the development of microwave observations faces unique time pressure. As a result, the work in Cycle 48r1 needs to be rapidly followed up, and the push towards all-surface assimilation comes at a very good time.

Outlook

We have already seen the benefit of adding observations of the atmosphere in difficult areas, such as high-latitude land and ocean. However, we expect to see even more benefit by directly exploiting the surface-related information in satellite radiances. This includes information on the sea-ice fraction, soil moisture and snow cover. If assimilated within a coupled modelling framework, better knowledge of these quantities could help improve forecasts well beyond the medium range. As mentioned already, there is still a huge amount of scientific and technical development needed to model the effect of these surfaces on satellite radiances.

Another development in Cycle 48r1 applies to the Advanced Technology Microwave Sounder (ATMS) instrument, which is only assimilated in the clear-sky framework and hence was not covered here. The ATMS development is to treat the surface as a diffuse scatterer, rather than a pure reflector. For future cycles, there is also a possibility to infer the skin temperature from microwave as well as from infrared observations. These are all useful advances but, like the changes documented in this article, they make simplifying assumptions about the surface. Currently we treat the surface as impenetrable to radiation, and possessing a single 'skin' temperature. To really move forward in all-surface microwave assimilation, we need more sophisticated modelling.

Rather than forming an impenetrable surface, sea-ice, snow and dry soils are partly transparent to microwave radiation, and the depth of the surface to which the radiation is sensitive depends strongly on the frequency. Hence, in the longer term we need to start including the top few metres of the surface (as well as vegetation) in our physical models of satellite-observed radiation, and representing the scattering, absorption, reflection and refraction of radiation in these materials.

However, a perfect physical model of radiation in the sea-ice, snow or soil layer would require information on the microstructural properties of the surface layers, for example the grain structure of snow or sand. These are often quantities to which satellite data has great sensitivity, but which are not yet represented in our models of the land-surface, snow or sea-ice. This will probably require us to make much more use of a data assimilation strategy known as parameter estimation, to estimate and to keep maps of these microstructural properties from one data assimilation cycle to the next.

We may also need to make increasing use of empirical modelling approaches, particularly machine learning, if the physical models are not good enough. These are all big challenges. Addressing them will be key to implementing the all-sky all-surface strategy over the next decade.

Further reading

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Israel uses ECMWF supercomputer to advance regional forecasting

Pavel Khain, Alon Shtivelman, Harel Muskatel, Anat Baharad, Leenes Uzan, Elyakom Vadislavsky, Eyal Amitai, Nurit Meir, Vladimir Meerson, Yoav Levi, Nir Stav (all Israel Meteorological Service), Bojan Kasic, Umberto Modigliani (both ECMWF)

The Israel Meteorological Service (IMS) has been operating a small high-performance computing (HPC) cluster of about 1,400 cores over the last decade. This local resource was sufficient for limited-area model high-resolution operational runs of the Eastern Mediterranean, but it did not allow any contribution to regional projects, extensive research in numerical weather prediction (NWP), or regional ensemble runs. In June 2019, ECMWF's Council approved an Optional Programme for Co-operating States that cannot apply for full Member State status, which enables them to use some of ECMWF's HPC resources. Over the last two years, IMS has used this option for research and the development of NWP for southeast Europe. It has also used it to contribute to international projects, such as the World Meteorological Organization's South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A).

High-resolution ensemble system

IMS is a member of the European Consortium for Small-scale Modelling (COSMO). However, due to the remote location of Israel from the other members, the COSMO-LEPS (COSMO Limited-Area Ensemble Prediction System) 7 km ensemble did not cover the region of Israel and its neighbouring countries. The Optional Programme allowed IMS to build a high-resolution ensemble forecasting system for the Eastern Mediterranean (25–39°E, 26–36°N), including Egypt, Cyprus, Lebanon, Israel and Jordan, on ECMWF's HPC facility. This COSMO ensemble suite (CO-IL-EPS) runs twice daily at the convection-permitting resolution of 2.5 km (Figure 1).

Initial data and lateral boundary conditions are taken from the ECMWF ensemble (ENS) and the deterministic high-resolution forecast (HRES). CO-IL-EPS includes 20 ensemble members and the deterministic model CO-IL2.5. Each member runs on 10 nodes of ECMWF's HPC facility for a total of 210 nodes for the entire suite. The spatial scale of geographic features in this region cannot be resolved in ECMWF's current HRES, which has a horizontal grid spacing of about 9 km, and even less in the current ENS, which has a horizontal grid spacing of about 18 km. The Judea hills, for example,

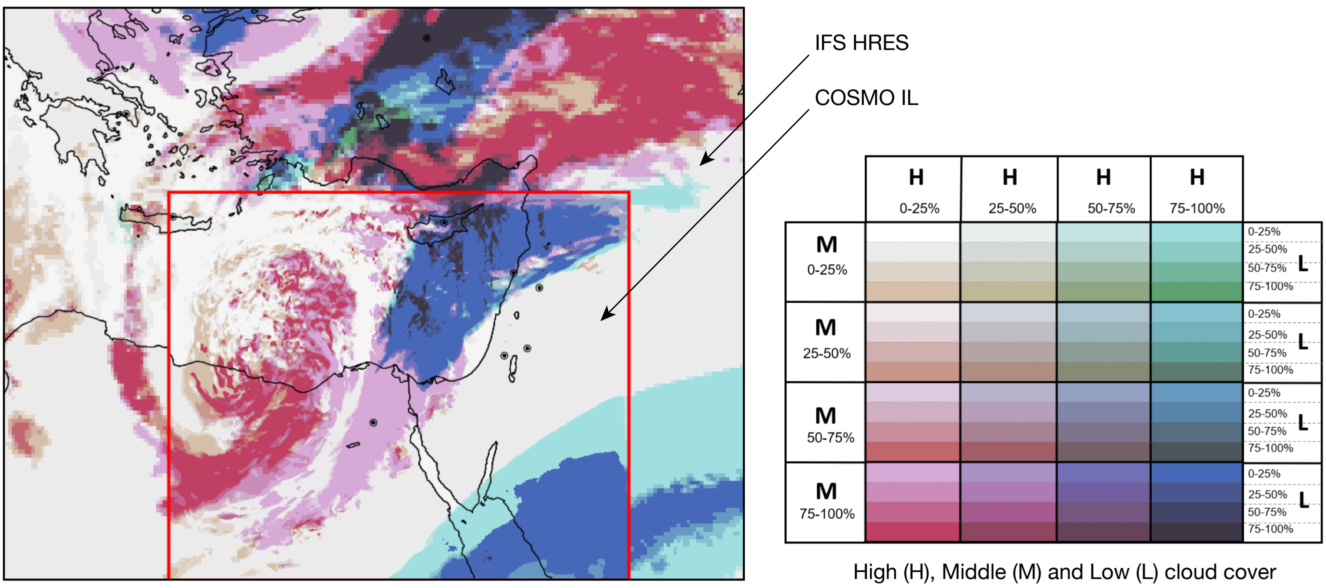

FIGURE 1 An example of the CO-IL-EPS domain nested in IFS boundary conditions. A 9-hour cloud coverage forecast valid at 21 UTC on 30 January 2022 is shown as displayed to the public on the IMS website *https://ims.gov.il/en/ModelMaps*.

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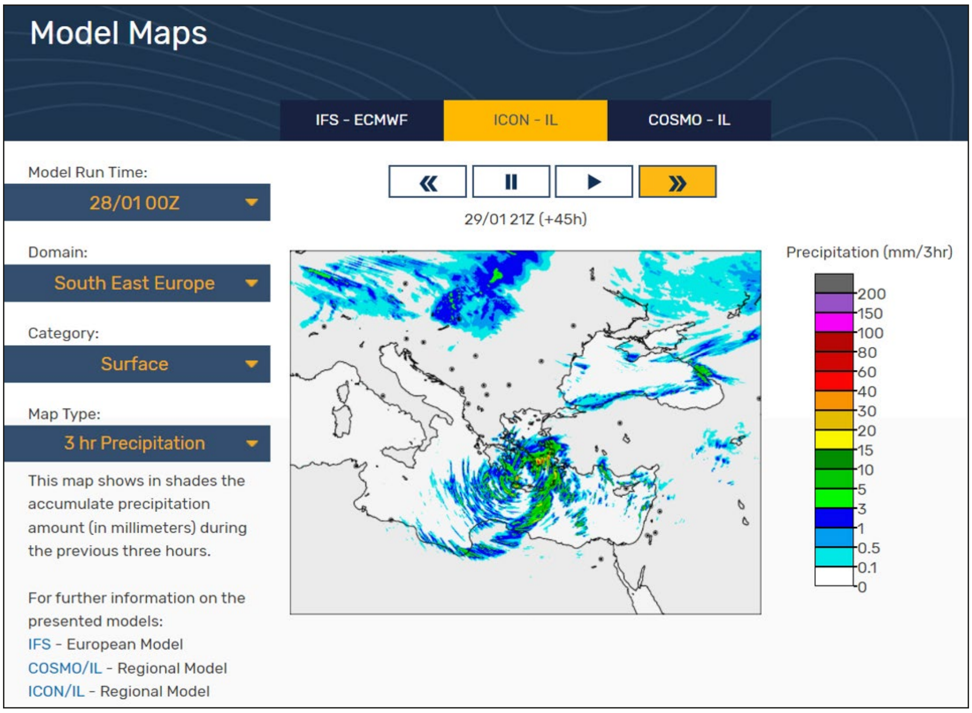

FIGURE 2 An example of an ICON-IL2.5 3-hourly precipitation forecast over southeast Europe on the IMS website: *https://ims.gov.il/en/ModelMaps*.

reach a height of more than 900 m above sea level, and the Dead Sea, at a distance of less than 15 km away, drops to more than 400 m below sea level. Some important meteorological processes are not described properly in ECMWF's forecasts, such as convective precipitation patterns (which are the typical precipitation mechanisms of this region). Thus, high-resolution probabilistic products gradually became essential tools for the IMS forecasters. Some of these products are also available to the other countries of the region through the IMS public website.

The SEE-MHEWS-A deterministic system

Alongside the COSMO ensemble system, IMS has set up another NWP suite based on the 2.5 km resolution ICON-LAM model (ICON-IL2.5) to provide deterministic weather forecasts for the southeast Europe region (4–45.5°E, 25.5–53°N, see Figure 2), as a part of the WMO's SEE-MHEWS-A project. This early warning system includes several ECMWF Member and Co-operating States and is intended to benefit 18 WMO Members of the region: Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Hungary, Israel, Jordan, Lebanon, North Macedonia, Republic of Moldova, Montenegro, Romania, Serbia, Slovenia, Turkey, and Ukraine. The SEE-MHEWS-A project supports national meteorological and hydrological services in fulfilling their mandate to provide timely and accurate warnings to minimise the impacts on people, infrastructure, and industry of hazardous weather events. For this suite, initial and lateral boundary conditions are taken from the IFS HRES. The suite runs twice per day with the model utilising 57 compute nodes since September 2020.

CO-IL-EPS and ICON-IL2.5 are also used for hydrological modelling. ICON-IL2.5 forecasts were used as input for the hydrological models of the SEE-MHEWS-A project pilot phase for the Vrbas River in Bosnia and Herzegovina and Vardar/Axios River in North Macedonia and Greece (see ECMWF Newsletter No. 170 for details of ECMWF's support for SEE-MHEWS-A). Both CO-IL-EPS and ICON-IL2.5 precipitation forecasts are used to drive the hydrological models of the Israeli Water Authority. First experience shows that specific precipitation rate percentiles of CO-IL-EPS are significantly less noisy than the deterministic forecasts and hence are particularly valuable for hydrological forecasting.

In addition to CO-IL-EPS and ICON-IL2.5 operational suites, ECMWF's HPC facilities are used by IMS for research purposes. New parametrizations and developments conducted in the framework of the COSMO consortium (*https://www.cosmo-model.org/*) are continuously being tested and verified. The operational suites are updated by improved versions once per year or even more frequently. Some of these scientific developments, which could not be conducted without ECMWF's HPC facilities, are highlighted in the last section.

Access to products

CO-IL-EPS and ICON-IL2.5 products are visualised on several platforms. ICON-IL2.5 forecasts are presented on the Common Information Platform (CIP) of the SEE-MHEWS-A project. The reader is referred to ECMWF Newsletter 170 for more details. Both CO-IL-EPS and ICON-IL2.5 are visualised on internal forecasting platforms used by IMS forecasters. Additional products are being continuously developed and added to these platforms almost on a weekly basis.

Most common synoptic maps of CO-IL-EPS, ICON-IL2.5, and the IFS are presented to the public on the IMS website (*https://ims.gov.il/en/ModelMaps*). Figure 2 shows an example of an ICON-IL2.5 3-hourly precipitation forecast over southeast Europe. Additional domains can be selected, including the Balkans, for the convenience of SEE-MHEWS-A countries.

CO-IL-EPS and ICON-IL2.5 raw data forecasts on a limited area are also freely accessible through IMS web services. This allows the private sector to develop products oriented for specific users. Moreover, ICON-IL2.5 forecasts are operationally distributed for the use of the Mediterranean cyclone tracking research as part of the COST Action CA19109 and for verification purposes as part of the COSMO consortium.

Visualisations using ECMWF tools

Utilisation of ECMWF's HPC facilities enabled the development of probabilistic products for CO-IL-EPS using ECMWF's meteorological software: the Metview meteorological workstation application, the Metview Macro language, and Magics meteorological plotting software.

Figure 3 shows an example of post-processing using these tools for probabilistic precipitation forecasting.

Panel (a) shows the radar and rain gauge composite for a heavy precipitation event that occurred in Tel Aviv on 4 January 2020 between 06 and 12 UTC. During this short event, 74 mm of rain fell within 2 hours (50 mm within half an hour), causing the drowning of a young couple in a flooded elevator in south Tel Aviv. Panels (b)-(d) present the CO-IL2.5 and CO-IL-EPS forecasts from 00 UTC on 3 January 2020. Panel (b) presents the CO-IL2.5 deterministic forecast, while panels (c) and (d) present the CO-IL-EPS probabilities to exceed 10 and 20 mm/6 h, respectively. Since precipitation is uncertain in space, the probability forecasts were upscaled to boxes of 12x12 km^2. This upscaling works as follows: if an ensemble member precipitation forecast passes a certain threshold at any grid point within such a box, the event is counted for the entire box. For estimating the probability of the event occurring within the box, the relative number of events is calculated. One can see that the probabilistic forecasts (unfortunately not operational during the event) predicted the location of the heavy precipitation better than CO-IL2.5.

Figure 4 shows the corresponding CO-IL-EPS precipitation meteogram for Tel Aviv, also obtained using ECMWF's tools. As can be seen, the 90% percentile of the ensemble reaches only 26 mm/6 h, but there was an ensemble member that showed 74 mm/6 h for Tel Aviv. Note that this meteogram is not upscaled. In contrast to Figure 3c,d, it represents precipitation forecasts in a 2.5x2.5 km^2 grid box over Tel Aviv.

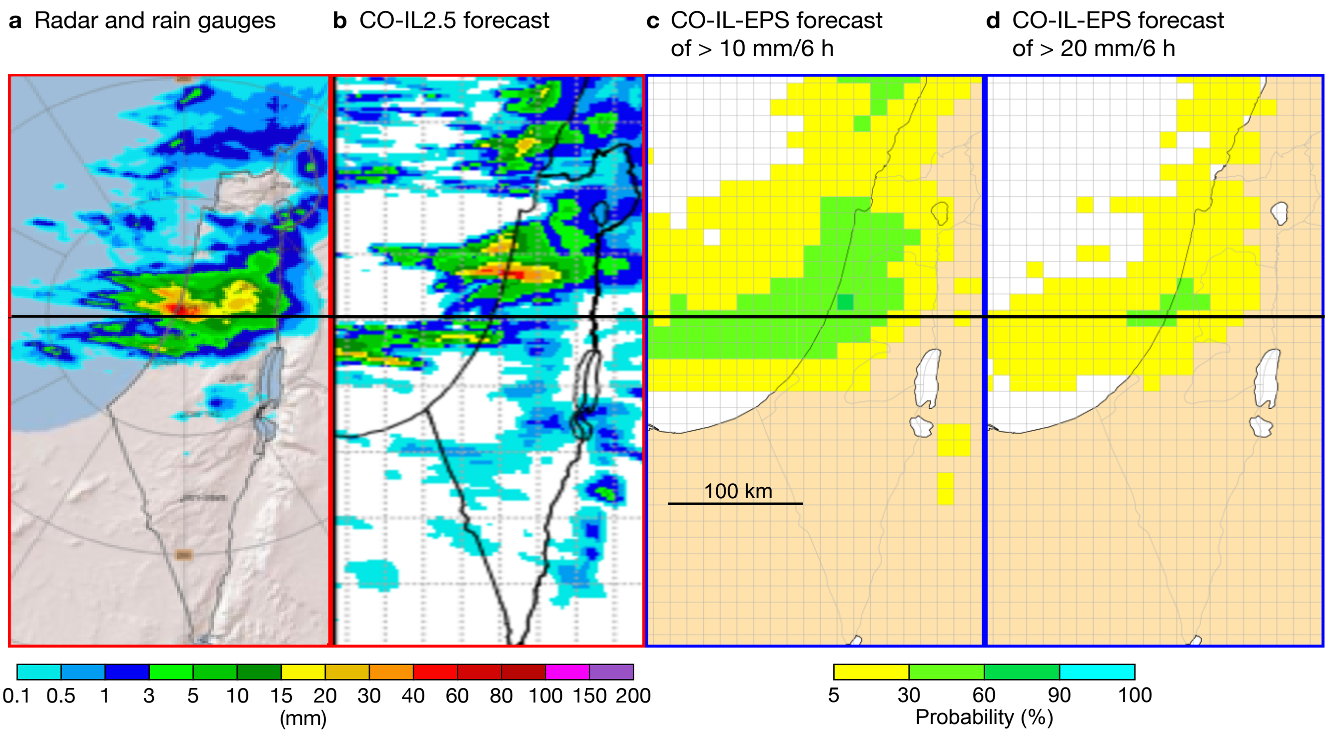

FIGURE 3 An example of using ECMWF's meteorological software for probabilistic precipitation forecasting. Panel (a) shows the radar and rain gauge composite for a heavy precipitation event that occurred in Tel Aviv on 4 January 2020 between 06 and 12 UTC. Panels (b)–(d) present the CO-IL2.5 and CO-IL-EPS forecasts from 00 UTC on 3 January 2020. Panel (b) presents the CO-IL2.5 deterministic forecast, while panels (c) and (d) present the CO-IL-EPS upscaled probabilities to exceed 10 and 20 mm/6 h, respectively.

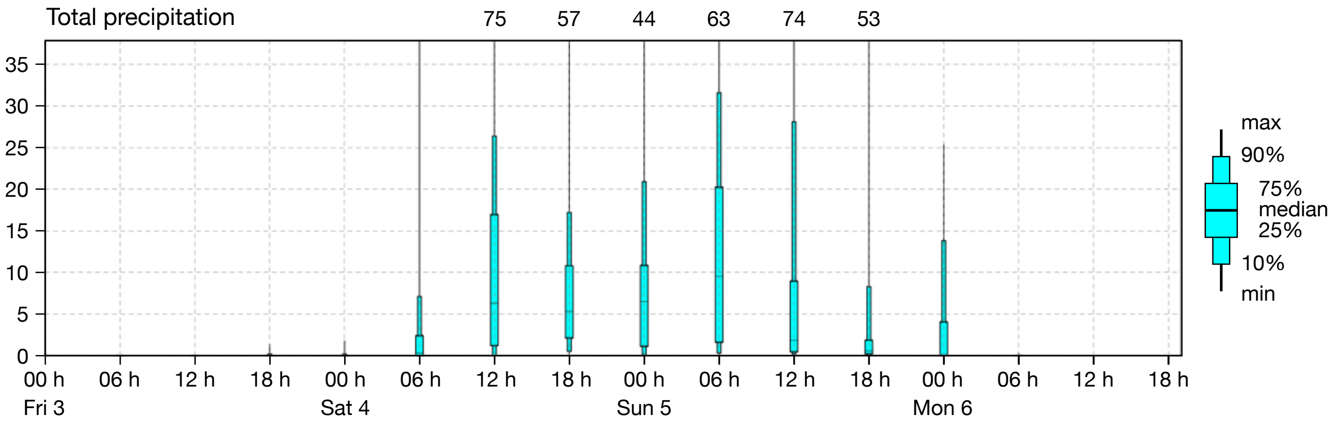

FIGURE 4 CO-IL-EPS precipitation meteogram for Tel Aviv (32.06°N, 34.76°E) obtained using ECMWF's meteorological software. The forecast was initiated at 00 UTC on 3 January 2020. The numbers on the top indicate the maximum total precipitation given by the respective ensemble forecast.

Verification

Before becoming operational, CO-IL-EPS and ICON-IL2.5 underwent extensive tuning focused on precipitation (Khain et al., 2021), near-surface parameters and cloudiness. Today these two systems, together with IFS HRES, show the highest skill among the models used at IMS. Figure 5 shows precipitation verification over Israel for the period from 1 March 2021 to 13 January 2022. The verification of selected CO-IL-EPS percentiles, the deterministic COSMO member (CO-IL2.5), ICON-IL2.5, and the IFS HRES was performed versus the IMS radar and rain gauges composite. Fractional Skill Score (FSS) was averaged over the spatial radiuses of 10, 20, 30 and 50 km. The thresholds of 10 mm/6 h and 20 mm/6 h are shown (panels a and b, respectively). While for low precipitation thresholds the deterministic models have an advantage over CO-IL-EPS percentiles, for 20 mm/6 h the 75% CO-IL-EPS percentile is the undisputed winner. For high

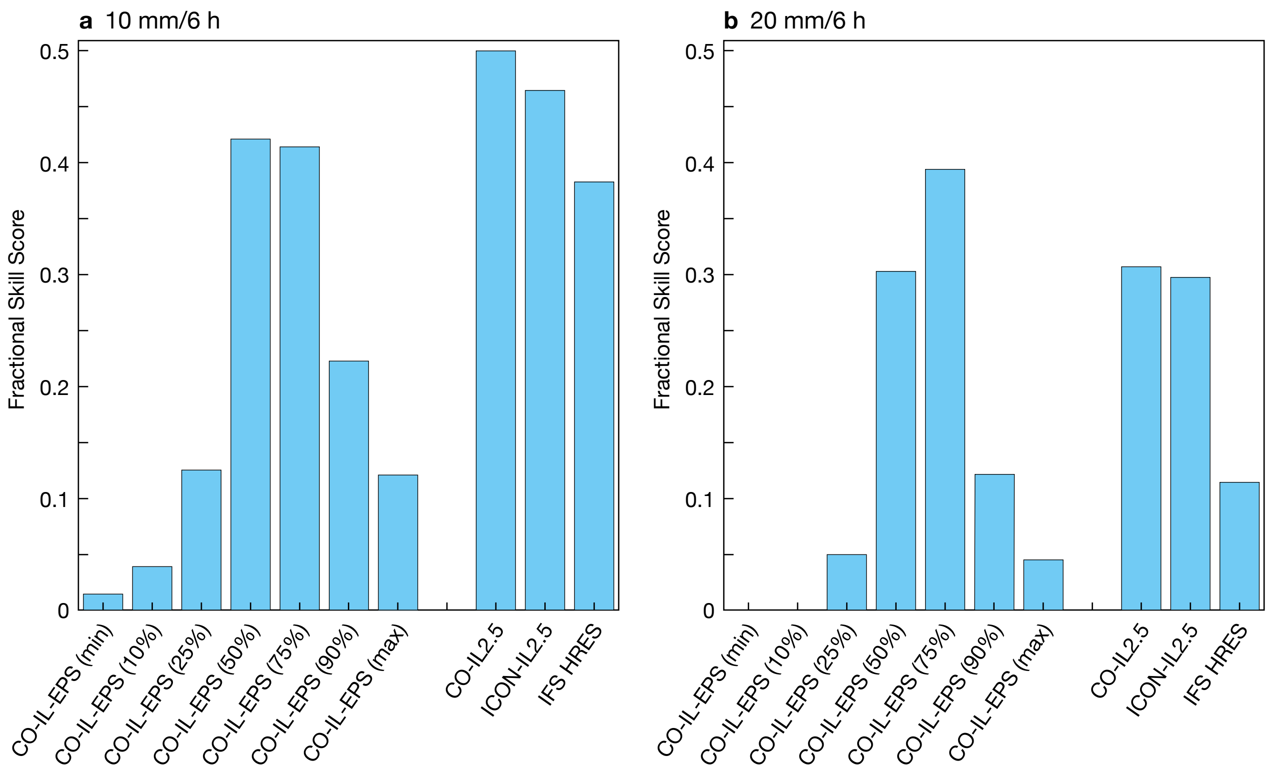

FIGURE 5 Precipitation verification over Israel for the period from 1 March 2021 to 13 January 2022. The Fractional Skill Score (FSS, between 0 and 1) is calculated for the thresholds of (a) 10 mm/6 h and (b) 20 mm/6 h for selected CO-IL-EPS percentiles, the deterministic COSMO member (CO-IL2.5), ICON-IL2.5 and IFS HRES. Forecast ranges up to 78 hours were verified. The FSS was averaged over the spatial radiuses of 10, 20, 30 and 50 km.

precipitation rates, the deterministic forecasts of the convection-permitting models are often noisy and uncertain in space and time. By contrast, this result shows that the 75% percentile of CO-IL-EPS is significantly less noisy and hence is an important tool for forecasts of severe weather and flooding.

The use of ECMWF's HPC facility for research

In addition to operational runs, ECMWF's HPC facility is used by IMS for its research and development efforts. Most of this research is conducted in the framework of the COSMO consortium and results in continuous improvement of CO-IL-EPS and ICON-IL2.5. Below we present several interesting examples.

Using CAMS forecasts of aerosols in NWP

Operational weather forecasting is in constant conflict between the desire for accuracy and the goal of delivering results in a timely manner. Computational resources are always limited, so usually expensive fully-coupled aerosol models, such as those provided by the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) run by ECMWF and ICON-ART, are replaced by a monthly aerosol climatology. On the other hand, radiation fluxes and cloud microphysics are critically affected by aerosol content. Solar radiation is scattered and absorbed by aerosols and can be significantly reduced in a highly polluted environment. Liquid and ice formation in clouds is also influenced by hydrophilic and hydrophobic aerosol content in the atmosphere. IMS has conducted research which proposes an intermediate solution to these issues by coupling predicted aerosol fields taken from the CAMS aerosol model with the ICON model. The idea is that at each time step ICON will use the CAMS predicted aerosols, interpolated in time and space, without the need to advect them in space. Therefore, the runtime stays almost identical to the aerosol climatology setup. In a first stage, the ECMWF radiation scheme (ecRad), which was recently introduced in ICON, was coupled with 3D predicted aerosol mixing ratios of CAMS. In the next step, we plan to implement the coupling of these aerosols with ice nucleation and water droplet activation schemes in the ICON model. The method was tested for the entire year 2020, using ECMWF's HPC facility.

Figure 6 shows the global radiation verification using 17 automatic radiation stations over Israel during the year 2020. Twelve relatively polluted days, i.e. days when the averaged PM2.5 measurements over Israel were more than three times higher than normal, were chosen for verification. The verification was performed during clear-sky conditions, where cloud cover both in models and observations was below 30%. Figure 6 compares the mean diurnal cycle of the global radiation in observations, the IFS HRES, CO-IL2.5, ICON-IL2.5 and the new version ICON-IL2.5-CAMS with CAMS aerosol coupling. The first 24 hours of each simulation were verified. For each model, the mean bias and the root-mean-square error (RMSE) are presented.

One can see that in ICON-IL2.5-CAMS the global radiation on polluted days was substantially improved. The 47.6 Wm^{-2} bias in ICON-IL2.5 was essentially removed, and the RMSE was reduced from 91.5 Wm^{-2} to 68.9 Wm^{-2}. Preliminary results show that during non-polluted days the global radiation improvement is less significant. We plan to verify that the

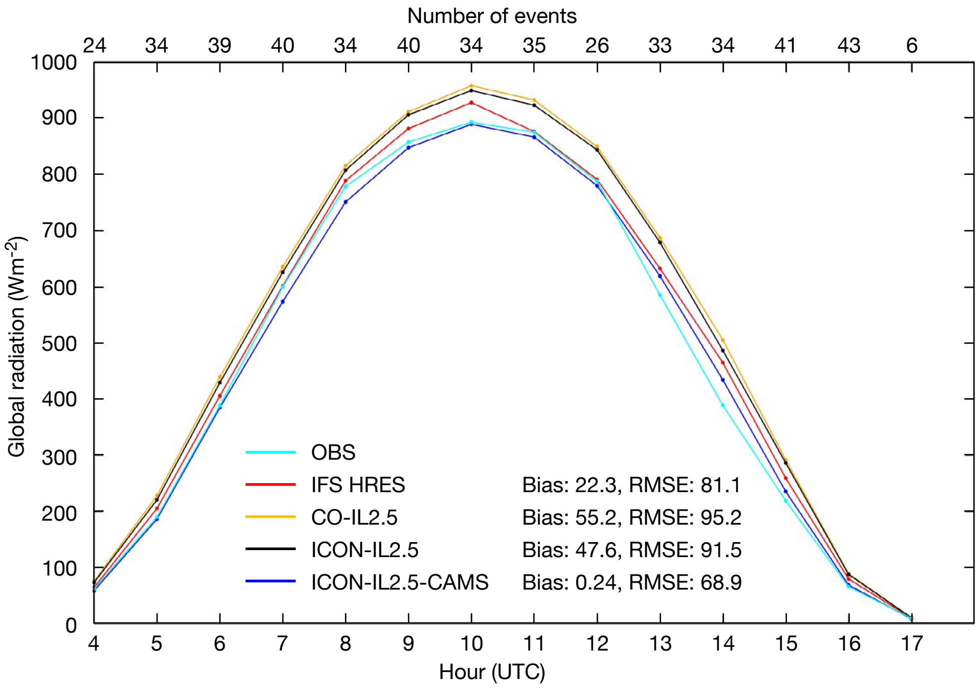

FIGURE 6 Global radiation verification over Israel for 12 clear-sky polluted days during the year 2020. The figure compares the mean diurnal cycle of the global radiation in observations (17 automatic radiation stations), the IFS HRES, CO-IL2.5, ICON-IL2.5 and the new version ICON-IL2.5-CAMS. The first 24 hours of each simulation were verified. For each model, the mean bias and RMSE are presented.

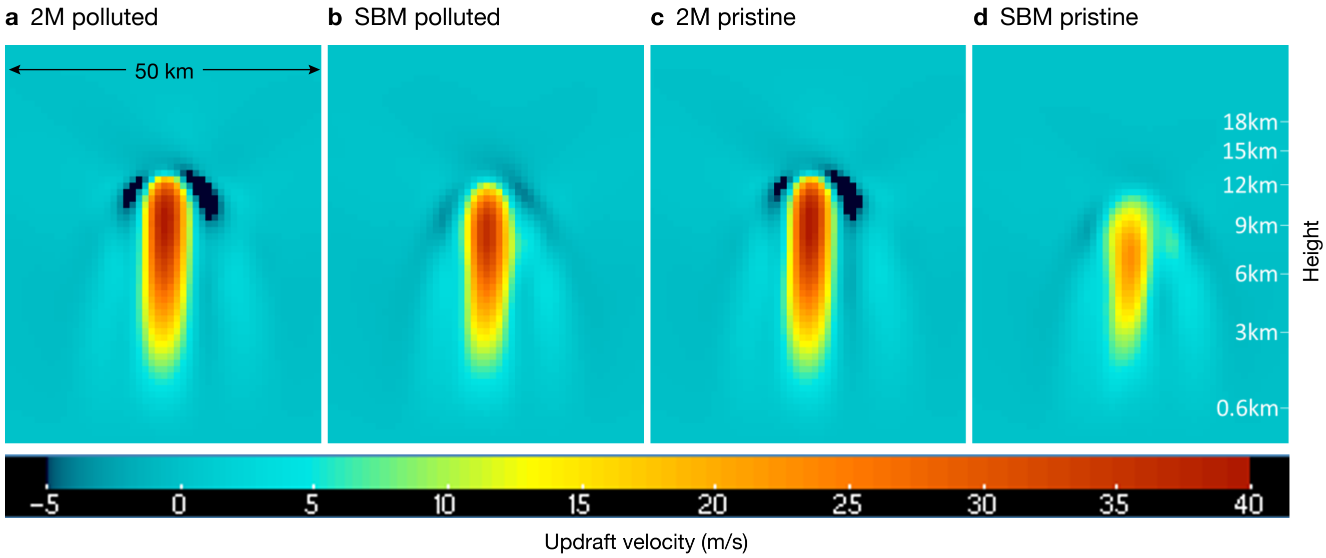

FIGURE 7 Vertical cross-section through the core of clouds of the updraft velocity after 30 minutes of cumulonimbus evolution in idealised 1 km resolution ICON simulations. Four versions are compared: (a) 2M in polluted conditions, (b) SBM in polluted conditions, (c) 2M in pristine conditions, (d) SBM in pristine conditions.

implementation of CAMS aerosols coupling in ICON-IL2.5 improves the radiation forecast over the entire southeast-Europe domain. The operational implementation of CAMS aerosols coupling in ICON-IL2.5 is planned for the summer of 2022 and will hopefully yield better forecasts for SEE-MHEWS-A project countries.

Modelling of clouds in ICON

A precise representation of clouds is important for NWP and climate models, and the aerosol impact on cloud microphysics is one of the key issues in current uncertainties in cloud modelling. Latent heat released in clouds is the main source of energy for many cloud-related phenomena as well as for global circulation. For the accurate modelling of cloud evolution, an accurate representation of cloud microphysics and consequently its interaction with aerosols is needed. The Spectral Bin Microphysics (SBM) scheme (Khain & Pinsky, 2018) is a state-of-the-art microphysical parametrization that is included in several models worldwide, such as the Weather Research and Forecasting (WRF) model, the Goddard Cumulus Ensemble model, the System for Atmospheric Modelling (SAM), etc. Microphysical processes in SBM are described by solving non-linear differential equations based on first principles. At each model grid point and time step, the particle size distributions (PSDs) are defined on mass grids containing several tens of bins. For each bin, various microphysical processes are calculated and the PSD is evolved with time. The main disadvantage of SBM is that this method is computationally time-consuming. This is because the microphysical equations are written for each mass bin, which means that SBM contains several hundred fields to be calculated.

Using ECMWF's HPC facility, the introduction and testing of SBM in ICON became possible. So far, we have introduced only the warm-phase part of SBM in ICON, and the introduction of the mixed-phase (i.e. ice processes) is planned.

Idealised 1 km resolution ICON simulations of cumulonimbus evolution were conducted under pristine and polluted conditions and compared with the two-moment (2M) microphysical scheme that is currently used in several advanced ICON implementations. Figure 7 shows a vertical cross-section, through the core of the clouds, of the updraft velocity after 30 minutes of cloud evolution. Panels (a) and (b) show 2M and SBM under polluted conditions, while (c) and (d) show them under pristine conditions. In contrast to 2M, SBM indicates strong sensitivity to aerosol concentration. Pristine conditions lead to a lower droplet concentration and higher supersaturation, faster drop growth and earlier beginning of intense collisions and raindrop formation. Compared to polluted conditions, the time during which droplets grow is small and hence less latent heat is released. This may explain the smaller development of the cloud and the smaller updraft velocities in the SBM simulation with pristine conditions.

Assimilation of OPERA radar network

The ICON model enables the assimilation of radar data in order to improve the forecast during the first few hours of the run. The radar data can be assimilated in the ICON-LAM via latent heat nudging (LHN) (Stephan et al., 2008), without a separate data assimilation system. During the model run the simulated precipitation is compared with the observed. In locations where there is a deficit in simulated precipitation, the vertical profiles of temperature and humidity are adjusted to account for the underestimation of latent heat release, which occurred as the precipitation formed. In locations where there is overestimation, the profiles are adjusted in the opposite direction.

As part of IMS activities for SEE-MHEWS-A, output from OPERA, EUMETNET's Operational Programme for the Exchange of Weather Radar Information, was assimilated. Using ECMWF's HPC facility during the second half of 2021, we could analyse the influence of the OPERA radar network assimilation on ICON-IL2.5 forecasts.

Figure 8 shows the verification of ICON-IL2.5 with and without OPERA assimilation during a severe flooding event over central Europe (12–15 July 2021). The verification was performed with OPERA data using the Equitable Threat Score for the threshold of 1 mm/h. In order to analyse the ability of the model to assimilate the OPERA data correctly, the LHN was performed during the entire simulation time. Obviously, this cannot be done in real time since the 'future' radar data is not available. Figure 8 nicely shows the benefit of OPERA data assimilation. The assimilation of the OPERA radar network in ICON-IL2.5 became operational in November 2021. Recently a new tuning of the LHN scheme, related to the bright band detection, was suggested by Germany's National Meteorological Service (DWD). It is planned to be tested in ICON-IL2.5.

Selection of driving ensemble members

Due to limitations of computer resources, high-resolution regional ensembles usually consist of a relatively small number of ensemble members. This number is often smaller than the size of the driving global ensemble. The specific selection of a subgroup of driving global ensemble members may influence the quality of the driven regional ensemble. IMS is currently performing research in the framework of the COSMO consortium on how to select a subgroup of the driving global ensemble members to optimise the performance of the driven regional ensemble. For initial and boundary conditions, the study uses ECMWF's ENS consisting of 50 members. The regional ensemble used is CO-IL-EPS. The conclusions are validated using two methods for model physics perturbations, namely the

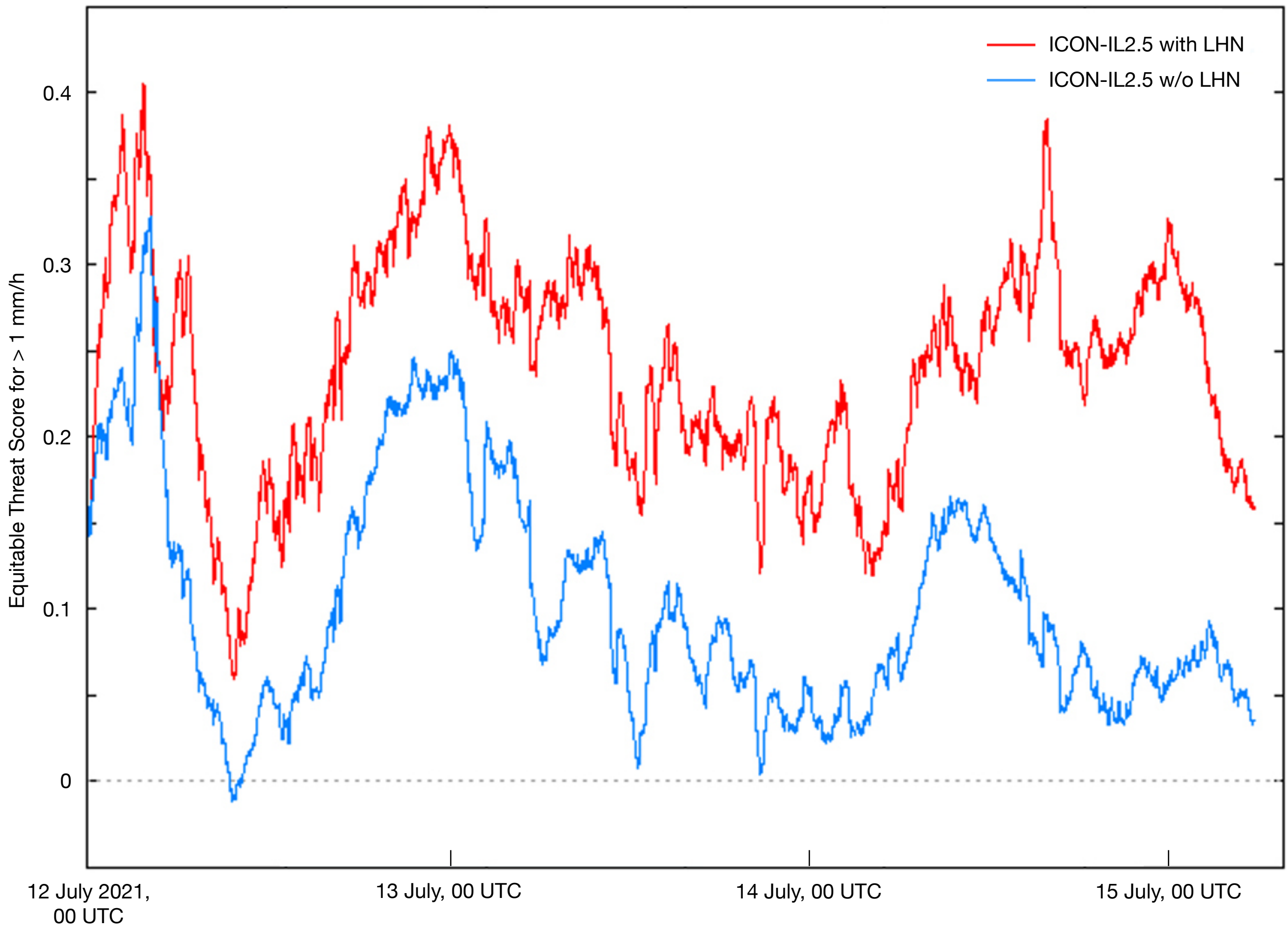

FIGURE 8 Verification of ICON-IL2.5 with (red) and without (blue) OPERA assimilation during a severe flooding event over central Europe (12–15 July 2021). The verification was performed with OPERA data using the Equitable Threat Score for the threshold of 1 mm/h. Higher values indicate better results.

Stochastically Perturbed Parametrization Tendencies (SPPT) also used at ECMWF, and the parameter perturbations (PP). Among 50 ENS members, 20 are chosen in different ways to drive the CO-IL-EPS. The corresponding 20 CO-IL-EPS members are then perturbed via SPPT or PP and verified against observations. Finally, the verification scores are compared, resulting in the optimal algorithm for the selection of 20 ENS members.

This research includes re-forecasting of several configurations of CO-IL-EPS over historical periods, which requires a substantial amount of computer resources. ECMWF's HPC facility is being used for this research, which otherwise could not be conducted.

Conclusions

The Israel Meteorological Service (IMS) has taken advantage of the Optional Programme for Co-operating States, which makes it possible to use ECMWF's HPC resources. IMS uses these resources to run a computationally demanding high-resolution COSMO ensemble system over the Eastern Mediterranean and a high-resolution ICON model over the southeast Europe region. Both suites are running operationally under time-critical option 2. These suites provide weather forecasts not only for use in IMS but also for the benefit of other weather services in the region. ICON forecasts are used within the WMO SEE-MHEWS-A project in southeast Europe, while COSMO ensemble forecasts are used as part of a collaboration with nearby countries. Both forecast systems are visualised on various platforms, and their products are being provided to the public and academia free of charge.

In addition to running operational systems, ECMWF's HPC facilities enable IMS to perform intensive research in the framework of the COSMO consortium. In addition to continuous improvement of the operational systems, these activities make it possible for IMS's research department to flourish. Many new collaborations have become possible, and scientific papers are being published.

Acknowledgements

Implementation of the CO-IL-EPS suite at ECMWF was supported by the weather service of the Italian Emilia-Romagna region, Arpae-SIMC, which runs COSMO-LEPS as a time-critical option 2 application at ECMWF and kindly offered to share its configuration with IMS.

The CO-IL-EPS and ICON-IL2.5 suites run at ECMWF are both using the FieldExtra post-processing software developed at the Federal Office of Meteorology and Climatology of Switzerland, MeteoSwiss, kindly provided to IMS in the framework of the COSMO consortium.

We acknowledge colleagues from Germany's National Meteorological Service, DWD, for constructive discussions and support in the implementation of CAMS predicted aerosols in ICON and the assimilation of OPERA via LHN.

IMS gratefully thanks ECMWF's Council for the opportunity to use ECMWF's HPC facilities and warmly thanks ECMWF staff for their extraordinary support.

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Technical Memoranda

895 **Brimicombe, C., T. Quintino, S. Smart, C. Di Napoli, R. Hogan, H.L. Cloke et al.**: Calculating the Cosine of the Solar Zenith Angle for Thermal Comfort Indices. *April 2022*

894 **Geer, A.J., K. Lonitz, D. Duncan & N. Bormann**: Improved surface treatment for all-sky microwave observations. *April 2022*

893 **Kanehama, T., I. Sandu, A. Beljaars, A. van Niekerk, N. Wedi, S. Boussetta, S. Lang, S. Johnson, L. Magnusson**: Evaluation and optimizaton of orographic drag in the IFS. *March 2022*

892 **Lopez, P., M. Matricardi & M. Fielding**: Validation of IFS+RTTOV/MFASIS solar reflectances against GOES-16 ABI obs. *March 2022*

890 **Janssen, P.A.E.M.**: Notes on shallow water extension of Miles Theory. *February 2022*

889 **Vitart, F., R. Emerton, M. Rodwell, M. Alonso-Balmaseda, T. Haiden, S. Johnson et al.**: Investigating biases in the representation of the Pacific sub-tropical jet stream and associated teleconnections (a UGROW sub-project). *January 2022*

EUMETSAT/ECMWF Fellowship Programme Research Reports

58 **Lonitz, K., A.J. Geer & N. Bormann**: Towards assimilating surface sensitive microwave channels over land. *March 2022*

ESA Contract Reports

Lonitz, K., C. Marquardt, N. Bowler & S. Healy: Final Technical Note of 'Impact assessment of commercial GNSS-RO data'. *November 2021*

ECMWF Calendar 2022

Apr 25–29	Training course: Advanced numerical methods for Earth system modelling
Apr 26–27	Finance Committee
Apr 27	Policy Advisory Committee
May 3–6	Training course: Machine learning for weather prediction
May 9–12	Workshop on model uncertainty
May 16–20	Training course: A hands-on introduction to NWP models
Jun 7–10	Using ECMWF's Forecasts (UEF2022)
Jun 11–12	Hackathon 2022: Visualising meteorological data
Jun 13–17	Online computing training week
Jun 28–29	Council
Sep 12–16	Annual Seminar 2022
Oct 3–5	Scientific Advisory Committee

Oct 3–6	Training course: Use and interpretation of ECMWF products
Oct 6	Advisory Committee of Co-operating States
Oct 6–7	Technical Advisory Committee
Oct 20–21	Finance Committee
Oct 21	Policy Advisory Committee
Oct 24–27	7th SPARC General Assembly
Oct 31–Nov 4	Sixth WGNE workshop on systematic errors in weather and climate models
Nov 14–17	ECMWF–ESA Workshop on Machine Learning for Earth Observation and Prediction
Dec 1–2	Council
Dec 5	Celebration of 30 years of the ensemble prediction system at ECMWF and symposium for Tim Palmer

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For any query, issue or feedback, please contact ECMWF's Service Desk at *servicedesk@ecmwf.int*.

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